Japanese Technology Evaluation Center

JTEC

JTEC Panel Report on

Microelectromechanical Systems in Japan

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September 1994

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JTEC PANEL ON MICROELECTROMECHANICAL SYSTEMS IN JAPAN

Sponsored by the National Science Foundation, the Advanced Research Projects Agency, the Air Force Office of Scientific Research, and the Department of Commerce of the United States Government

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INTERNATIONAL TECHNOLOGY RESEARCH INSTITUTE JTEC/WTEC PROGRAM

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JTEC/WTEC's mission is to inform U.S. policy makers, strategic planners, and managers of the state of selected technologies in foreign countries in comparison to the United States. JTEC/WTEC assessments cover basic research, advanced development, and applications/commercialization. Small panels of about six technical experts conduct JTEC/WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in universities and in industry/government labs.

The ITRI staff at Loyola College help select topics, recruit expert panelists, arrange study visits to foreign laboratories, organize workshop presentations, and finally, edit and disseminate the final reports.

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ABSTRACT

This report summarizes recent activities in the development of microelectromechanical systems (MEMS) in Japan. For the purposes of this study, "MEMS" means batch-fabricated miniature devices that convert physical parameters to or from electrical signals and that depend on mechanical structures or parameters in important ways for their operation. The report covers advanced materials and process technology; sensors and sensing microstructures; microactuators and actuation mechanisms; sensor-circuit integration and system partitioning; advanced packaging, microassembly, and testing technologies; and MEMS design techniques, applications, and infrastructure. The panel found that Japanese industry is emphasizing approaches to MEMS that are similar to those taken by U.S. industry (i.e., approaches based on silicon integrated-circuit technology); these efforts are comparable in their level of development to those in the United States. However, the ten-year, $250 million, MITI-sponsored program in micromachines emphasizes the miniaturization of more traditional (nonlithographic) machining processes, an area in which there is no comparable U.S. effort. Packaging technology and applications for batch-fabricated MEMS devices is considered a major challenge in both countries. The panel concluded that these and other issues will require global leadership and international cooperation to realize the benefits of MEMS in a timely way.

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FOREWORD

The National Science Foundation has been involved in funding technology assessments comparing the United States and foreign countries since 1983. A sizable proportion of this activity has been in the Japanese Technology Evaluation Center (JTEC) and World Technology Evaluation Center (WTEC) programs. We have supported more than thirty JTEC and WTEC studies over a wide range of technical topics.

As U.S. technological leadership is challenged in areas of previous dominance, such as aeronautics, space, and nuclear power, many governmental and private organizations seek to set policies that will help maintain U.S. strengths. To do this effectively requires an understanding of the relative position of the United States and its competitors. The purpose of the JTEC/WTEC program is to assess research and development efforts ongoing in other countries in specific areas of technology, to compare these efforts and their results to U.S. research in the same areas, and to identify opportunities for international collaboration in precompetitive research.

Many U.S. organizations support substantial data gathering and analysis efforts directed at nations such as Japan. But often the results of these studies are not widely available. At the same time, government and privately sponsored studies that are in the public domain tend to be "input" studies. That is, they provide enumeration of inputs to the research and development process, such as monetary expenditures, personnel data, and facilities, but do not provide an assessment of the quality or quantity of the outputs obtained.

Studies of the outputs of the research and development process are more difficult to perform because they require a subjective analysis performed by individuals who are experts in the relevant technical fields. The National Science Foundation (NSF) staff includes professionals with expertise in a wide range of disciplines. These individuals provide the technical expertise needed to assemble panels of experts that can perform competent, unbiased, technical reviews of research and development activities.

Specific technologies, such as telecommunications, biotechnology, microelectromechanical systems, and nuclear power, are selected for study by government agencies that have an interest in obtaining the results of an assessment and are able to contribute to its funding. A typical assessment is sponsored by two to four agencies. In the first few years of the program, most of the studies focused on Japan, reflecting concern over Japan's growing economic prowess. Studies were largely defined by a few federal mission agencies that contributed most of the funding, such as the Department of Commerce, the Department of Defense, and the Department of Energy.

The early JTEC methodology involved assembling a team of U.S. experts (usually six people from universities, industry, and government), reviewing the extant literature, and writing a final report. Within a few years, the program began to evolve. First, we added site visits. Panels traveled to Japan for a week visiting twenty to thirty industrial and research sites. Then, as interest in Japan increased, a larger number of agencies became involved as cosponsors of studies. Over the ten-year history of the program, fifteen separate branches in six agencies of the federal government (including NSF) have supported JTEC and WTEC studies.

Beginning in 1990, we began to broaden the geographic focus of the studies. As interest in the European Community (now the European Union) grew, we added Europe as area of study. With the breakup of the former Soviet Union, we began organizing visits to previously restricted research sites opening up there. These most recent WTEC studies have focused on identifying opportunities for cooperation with researchers and institutes in Russia, the Ukraine, and Belarus, rather than on assessing them from a competitive viewpoint.

In the past four years, we have also begun to considerably expand dissemination efforts. Attendance at JTEC/WTEC workshops (in which panels present preliminary findings) has increased, especially industry participation. Representatives of U.S. industry now routinely number 50 percent or more of the total attendance, with a broad cross section of government and academic representatives making up the remainder. JTEC and WTEC studies have also started to generate increased interest beyond the science and technology community, with more workshop participation by policymakers and better exposure in the general press (e.g., *Wall Street Journal*, *New York Times*). Publications by JTEC and WTEC panel members based on our studies have increased, as have the number of presentations by panelists at professional society meetings.

The JTEC/WTEC program will continue to evolve in response to changing conditions in the years to come. We are now considering new initiatives aimed at the following objectives:

- Expanded opportunities for the larger science and technology community to help define and organize studies. This may be accomplished through a proposal competition in which NSF would invite universities and industry (preferably working together) to submit proposals for JTEC and WTEC studies. These would then be peer reviewed much as NSF reviews research proposals.

- Increased industry sponsorship of JTEC and WTEC studies. For example, NSF recently funded a team organized by the Polymer Science & Engineering Department at the University of Massachusetts (Amherst) to visit Japan for two weeks studying biodegradable plastics and polymers R&D there. Twelve industrial firms put up over half of the funds.

- Providing a broader policy and economic context to our studies. This is directed at the need to answer the question "So what?" that is often raised in connection with the purely technical conclusions of many JTEC and WTEC panels. What are the implications for U.S. industry and the economy in general of the technical results? We are adding an economist to an upcoming JTEC study on optoelectronics in Japan as a new effort to address these broader questions.

In the end, all government-funded programs must answer the following question: *How has the program benefitted the nation?* A few of the benefits of the JTEC/WTEC program follow:

- JTEC studies have contributed significantly to U.S. benchmarking of the growing prowess of Japan's technological enterprise. Some have estimated that JTEC has been responsible for over half of the major Japanese technology benchmarking studies conducted in the United States in the past decade. JTEC reports have also been widely cited in various competitiveness studies.

- These studies have provided important input to policymakers in federal mission agencies. JTEC and WTEC panel chairs have given special briefings to senior officials of the Department of Energy, the NASA Administrator, and even the President's Science Advisor.

- Studies have been of keen interest to U.S. industry, providing managers with a sense of the competitive environment internationally. Members of the recently completed study on satellite communications have been involved in preliminary discussions concerning the establishment of two separate industry/university consortia aimed at correcting the technological imbalances identified by the panel in its report.

- Information from JTEC and WTEC studies also has been valuable to both U.S. and foreign researchers, suggesting a potential for new research topics and approaches, as well as opportunities for international cooperation. One JTEC panelist was recently told by his Japanese hosts that, as a result of his observations and suggestions, they have recently made significant new advances in their research.

- Not the least important is the educational benefit of the studies. Since 1983 over 170 scientists and engineers from all walks of life have participated as panelists in the studies. As a result of their experiences, many have changed their viewpoints on the significance and originality of foreign research. Some have also developed lasting relationships and ongoing exchanges of information with their foreign hosts as a result of their participation in these studies.

As we seek to refine the JTEC/WTEC program in the coming years, improving the methodology and enhancing the impact, we will still be operating from the same basic premise that has been behind the program from its inception: the United States can benefit from a better understanding of cutting-edge research that is being conducted outside its borders. Improved awareness of international developments can significantly enhance the scope and effectiveness of international collaboration and thus benefit all of our international partners in collaborative research and development efforts.

Paul J. Herer
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EXECUTIVE SUMMARY

BACKGROUND

This report summarizes recent activities in the development of microelectromechanical systems (MEMS) in Japan. It has been prepared under the sponsorship of several U.S. governmental agencies and under the auspices of the Japanese Technology Evaluation Center (JTEC). The report is felt to be particularly important at the present time because of the high potential impact of this emerging field on many areas critical to national needs, including health care, industrial automation (including automated semiconductor manufacturing), automotive systems (both vehicles and smart highways), global environmental monitoring, environmental controls, defense, and a wide variety of consumer products. It is also important because of the many contributions Japan has made to this area in the past and its aggressive commitment to its future. The report will summarize important recent technological progress in Japan in MEMS and approaches being taken there to overcome the remaining challenges confronting this area. While, as should be expected, there are many similarities to the general nature of programs in the United States, there are also some important differences, particularly in approach and emphasis; these are discussed in some detail. The views expressed here are necessarily those of the panel members alone, but are nonetheless thought to accurately reflect the current situations in Japan and the United States, both in academia and in industry.

For the purposes of this study, "MEMS" means batch-fabricated miniature devices that convert physical parameters to or from electrical signals and that depend on mechanical structures or parameters in important ways for their operation. Thus, this definition includes batch-fabricated monolithic devices such as accelerometers, pressure sensors, microvalves, and gyroscopes fabricated by micromachining or similar processes. Also included are microassembled structures based on batch-fabricated parts, especially when batch assembly operations are used, but the study does not focus on individually-fabricated devices that are unlikely to see wide use. It is expected that electronic signal processing will exist in most future MEMS, which implies that they will be composed of sensors, actuators, and integrated electronics. Trends to increasing levels of integration are driving toward realization such devices as monolithic chips or multichip modules. These microsystems will be critically important as they extend microelectronics beyond its traditional functions of information processing and communications into the additional areas of information gathering (sensing) and control (actuation). Semiconductor Equipment and Materials International (SEMI) has estimated that the world market for MEMS devices could reach $8 billion by the turn of the century. This does not count the much larger markets for finished products that could be leveraged by the price/performance advantages of MEMS devices incorporated into such products.

New materials and processes such as LIGA (see Glossary, Appendix E, for definition) were also an important part of the study, along with testing, packaging, and many issues associated with the design and developmental infrastructures needed for MEMS. Image sensors, chemical sensors, and purely thermal or magnetic devices, however, are not covered specifically in this report even though they are often based on technology and generic microstructures developed for MEMS and are often lumped under this acronym.

APPROACH

In conducting this study, activities in MEMS were divided into the following six areas:

- Advanced materials and process technology
- Sensors and sensing microstructures
- Microactuators and actuation mechanisms
- Sensor-circuit integration and system partitioning
- Advanced packaging, microassembly, and testing technologies
- MEMS design techniques, applications, and infrastructure

A total of seventy-four specific questions covering these six areas were prepared and mailed to twenty-three organizations in Japan (five government agencies or laboratories, six university laboratories, and twelve industrial sites) that were known to be working in MEMS-related areas and were felt to represent a cross section of current activity there. The questions were intended to raise important issues as a framework for subsequent discussions. In some cases, they were addressed specifically in the ensuing site visits in Japan, while in others the answers became apparent through formal and informal discussions that occurred on site. The panel spent one week in Japan visiting these twenty-three organizations (listed under Appendix C in the Table of Contents).

CONCLUSIONS

Table E.1 summarizes the JTEC panel's qualitative comparisons of Japanese MEMS R&D and applications activities with those in the United States.

The other principal conclusions of this study can be summarized as follows:

- Overall, Japanese industry is emphasizing approaches to MEMS that are similar to those taken by U.S. industry. These efforts are primarily based on silicon integrated-circuit technology and are focused on sensor applications. Japanese industrial capabilities in these areas are comparable to those in the United States.

TABLE E.1
Japan Compared to United States in Microelectromechanical Systems

	R & D		Applications	
	Status	Trend	Status	Trend
Advanced Materials & Processes				
lithography-based	—	⇑	O	⇒
non-lithography-based	+	⇑	+	⇑
Sensors & Sensing Microstructures	—	⇒	O	⇒
Microactuators				
lithography-based	—	⇓	—	⇓
non-lithography-based	+	⇑	+	⇑
Sensor-Circuit Integration &				
System Partitioning	—	⇒	O	⇒
Advanced Packaging, Microassembly,				
and Testing	O	⇑	O	⇑
Design Techniques	O	⇒	O	⇒

Legend:

+	Japan now ahead
O	Japan and U.S. now about even
-	Japan now behind
⇑	Japan gaining ground
⇒	Japan and U.S. progressing equally
⇓	Japan losing ground

o Substantial efforts to develop microactuators, microelectromechanical systems, and micromachines based on advanced lithographic processes exist in both countries. The United States is perceived to have the lead in these areas and in sensor-circuit integration, although the Japanese programs are quite competitive, especially in realizing commercial products.

o Research efforts on MEMS in Japanese universities are generally less well equipped than their U.S. counterparts and involve a more diverse array of approaches and processes. While university research is one of the real strengths of MEMS in the United States, the research potential of Japanese universities is probably underdeveloped and underutilized.

- Japan is perceived to lead in nonlithographic approaches to MEMS, although it is not clear that such approaches can achieve the batch-fabrication and compatibility with electronic signal processing that most high-volume applications would appear to require.

- The ten-year large-scale ($250 million) MITI-sponsored program in micromachine technology (formally titled the Micromachine Technology Project) emphasizes the miniaturization of more traditional (nonlithographic) machining processes and involves projects chosen to complement efforts already underway in industry. This program involves twenty-four Japanese companies, many of which have larger ongoing internally-funded programs in MEMS-related areas. Still other Japanese companies are strongly involved in MEMS, but do not participate in the MITI program. MITI is encouraging participation by foreign companies in its micromachine technology program, which currently has one Australian and two U.S. participants.

- Packaging technology is application-specific and is considered a major challenge in both countries. Japanese efforts in low-temperature wafer-to-wafer bonding are applicable to the realization of wafer-level device encapsulation/packaging as well as to the creation of advanced batch-fabricated microstructures.

- The infrastructures for MEMS development in the United States and Japan are different, but both are effective. Strengths of the Japanese efforts include the relatively high involvement of industrial residents at Japanese universities and the ability in Japan to set long-range goals and establish multidisciplinary multiorganizational teams to accomplish them.

Microelectromechanical systems promise to lead microelectronics into important new areas that will be revolutionized by low-cost data acquisition, signal processing, and control. These microsystems are expected to have a profound impact on society, but their development will require synergy among many different disciplines that may be slow to develop. Global leadership and cooperation will be required to realize the benefits of MEMS in a timely way. This report examines recent activities in Japan in tackling these problems and contrasts them with U.S. approaches and perceptions. In so doing, the authors hope that the report will further the development of the field to hasten the utilization of MEMS by the global community.

CHAPTER 1

MICROELECTROMECHANICAL SYSTEMS DEVELOPMENT IN JAPAN

Kensall D. Wise

INTRODUCTION

The field of MEMS has been recognized internationally only within the last few years, although it is rooted in efforts on sensors and actuators that go back thirty years or more (Wise 1991; Wise and Najafi 1991). The field has been driven by the rapid global progress in the field of microelectronics, where solid-state microprocessors and memory have revolutionized many aspects of instrumentation and control, and have facilitated explosive growth in data processing and communications for more than three decades. Many of the emerging application areas for microelectronics, however, deal with nonelectronic host systems, and thus require that parameters such as pressure or flow be measured and converted to electrical signals that can be processed by computer. After the necessary control decisions are made electronically, the resulting electronic signals can then be fed to actuators to control the parameters of the host system. Figure 1.1 shows the organization of such a control loop, which represents a general microelectromechanical system. It is the promise of MEMS that such systems will eventually find realization in highly integrated, low-cost, and very accurate forms.

By the early 1980s, progress in microelectronics had reduced the cost of a microprocessor to less than that of a typical silicon sensor; today the peripheral functions of sensing and actuation continue to represent the principal bottlenecks in the application of microelectronics to many emerging systems, not only in terms of cost but in terms of reliability and accuracy as well. It is thus evident that continued progress in sensors, actuators, and MEMS is likely to exert considerable leverage on the microelectronics industry beyond the considerable direct markets for these products. Progress will enable the use of microprocessors and memory that otherwise could not be applied. And the direct markets themselves are significant. Indeed, Semiconductor Equipment and Materials International (SEMI) recently noted (SEMICON 1993) that SEMI's mission "now includes not only a commitment to semiconductor technology but to other related industries such as micromachining (MEMS), multichip module, and flat panel display technologies (FPD).... By 1999, it is expected that micromachining and flat panel displays will add some 25 percent more to the market opportunities in dollar terms, giving the total between semiconductors, MEMS and FPD over a $100 billion dollar market potential." SEMI also noted that "MEMS are integrated sensors, actuators, and electronics fabricated with processes similar to those used for ICs [integrated circuits].... By the turn of the century, worldwide sales of MEMS devices could reach $8 billion."

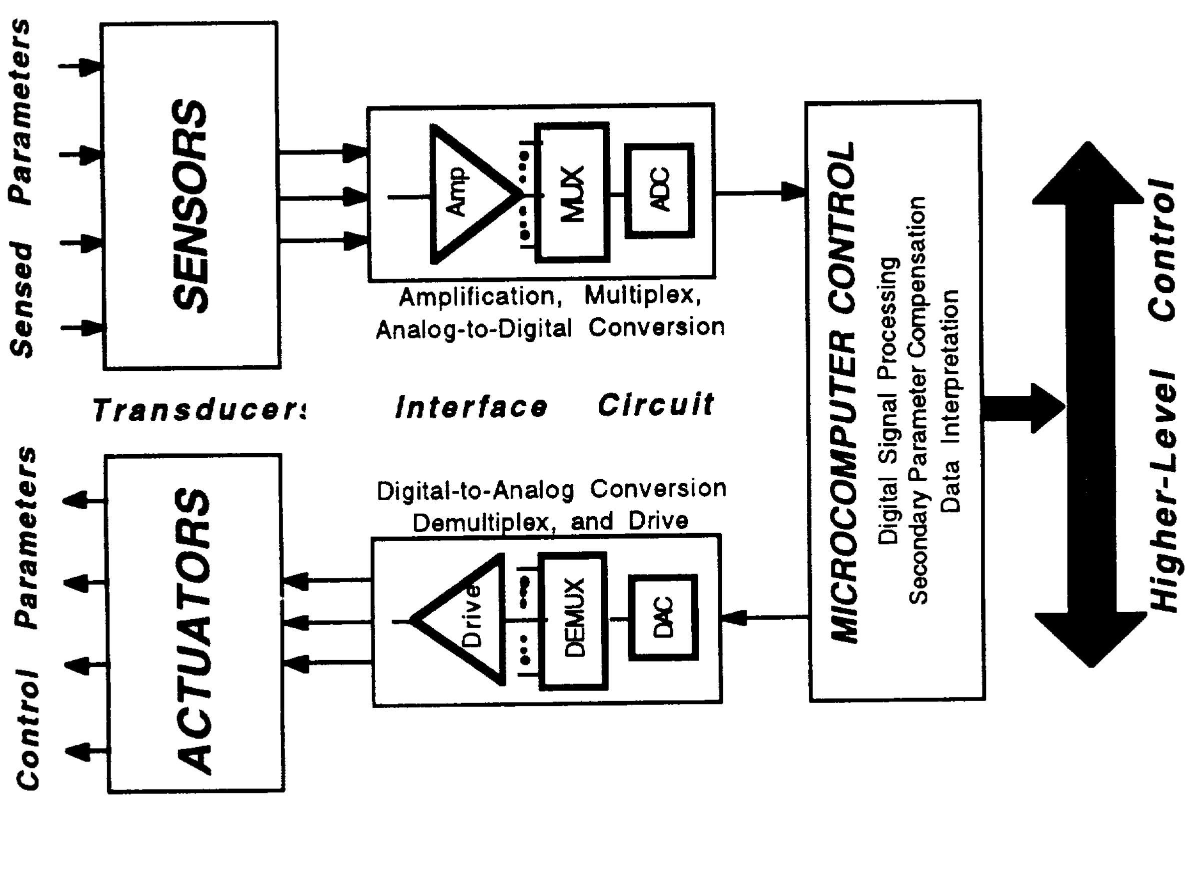


Figure 1.1. Structure of a sensor/actuator control loop typical of evolving microelectromechanical systems. In MEMS, such loops will become highly integrated, reduced in some cases to the level of a single chip.

The role of MEMS in extending electronic signal processing to new types of systems was recently emphasized by K.J. Gabriel (1993) as depicted in Figure 1.2.

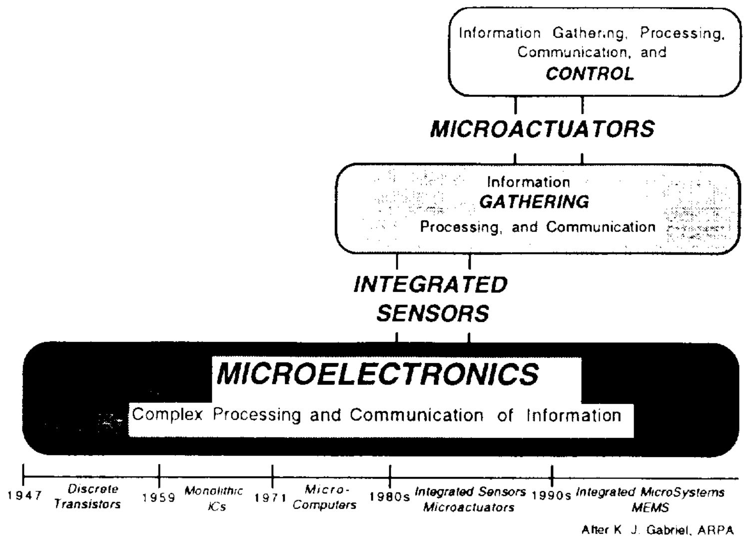


Figure 1.2. The role of sensors and actuators in extending integrated microsystems beyond information processing and communication into information gathering and control.

The addition of integrated sensors to microelectronics allows information *gathering* to occur in highly integrated systems in addition to the more traditional roles of information *processing and communication.* Beyond that, the emergence of microactuators promises the ability to exert significant measures of *control* over nonelectronic events at very small sizes. The ability to do sensing and actuation at low cost in distributed systems promises to significantly extend microelectronic applications. However, there is another dimension to MEMS. Microelectronics, most integrated sensors, and many microactuators are based on the ability to batch-fabricate miniature component assemblies. In electronics, this has permitted an explosion of information processing capability that is well known. However, there is a possible parallel path for purely micromechanical parts and subassemblies in which these devices are also batch-fabricated. While many mechanical systems in the macroworld must be large to perform their tasks, there are other applications involving functions at the millimeter or micron levels where perhaps they do not. This parallel path is shown in Figure 1.3. One portion of the current Japanese effort is addressing such micromechanical systems, including micromachines, which represent an extension of both micromechanics and MEMS. Indeed, while in the United States most of the players in the MEMS field originated in the lithography-based world of microelectronics, a larger fraction of the Japanese efforts is derived from mechanical engineering and is based on the miniaturization of more conventional machining processes, including microgrinding and electro-discharge machining (EDM). These nonlithographic processes would presumably be extended to high-volume applications through their use in creating master molds, which could be used for parts replication.

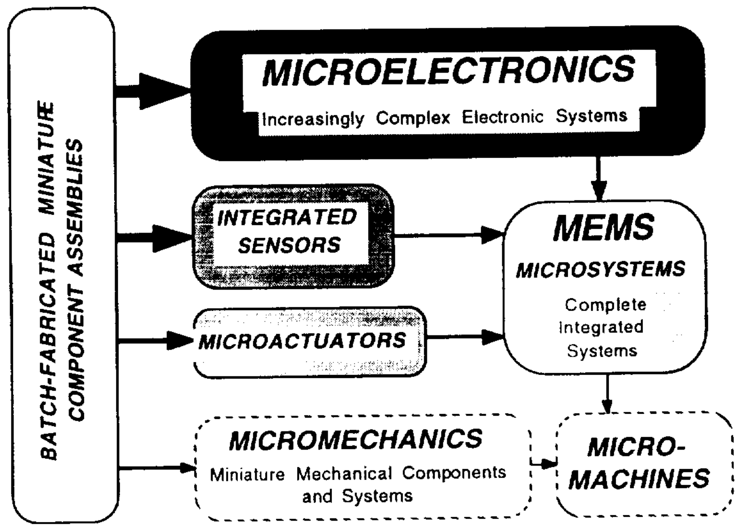


Figure 1.3. Extension of batch-fabrication concepts to microelectronics, MEMS, micromechanics, and micromachines.

Figure 1.4 gives an example of a miniature micromotor and MEMS gear train fabricated at the University of Wisconsin using the LIGA process (Guckel et al. 1991). In LIGA, X-ray lithography is used to form very precise high-aspect ratio patterns in a thick polymer (photoresist), which is then used as a mold to be filled using electroplating. When nickel is used as the plated material, the resulting parts can be driven magnetically. Japanese efforts in LIGA will be discussed in Chapter 2.

For our purposes we will define "MEMS" to mean batch-fabricated miniature devices that convert physical parameters to or from electrical signals and which depend on mechanical structures or parameters in important ways for their operation. Thus, we include batch-fabricated monolithic devices such as accelerometers, pressure sensors, microvalves, and gyroscopes fabricated by micromachining or similar processes. We also include microassembled structures based on batch-fabricated parts, especially when batch assembly operations are used; but we have elected not to focus on individually-fabricated devices which are unlikely to see wide use. It is expected that an interface to electronic signal processing will exist in most MEMS, which implies that they will include sensors, actuators, or (in most cases) both. New materials and processes such as LIGA were an important part of this JTEC study along with testing, packaging, and many issues associated with the design and development infrastructures needed for MEMS. Image sensors, chemical sensors, and purely thermal or magnetic devices, however, are not covered specifically in this report even though they often involve technology and generic microstructures that are similar to those in MEMS and are often lumped under this acronym. In this sense, "MEMS" is a bit of a misnomer and a more general term is needed. Indeed, the most frequent answer to the question of "After pressure sensors and accelerometers, what is the next major sensor based on MEMS that will be mass produced in high volume?" was "chemical sensors for medical applications."

Figure 1.4. Nickel micromotor and gear train formed using the LIGA process at the University of Wisconsin (Guckel et al. 1991). Such structures combine extreme precision with high aspect ratios, can be driven magnetically, and provide one example of MEMS. The rotor diameter here is 150 μm. Magnetic micromotors have been driven at rates exceeding 50,000 rpm.

As noted above, MEMS began as an outgrowth of expanding efforts to realize sensors and actuators using solid-state technology. During the past thirty years, considerable strides have been made in this area (Wise 1991; Wood, Han, and Kruse 1992). Beginning with visible image sensors in the mid-1960s and then pressure sensors in the 1970s, most efforts to realize sensors have drawn extensively from integrated circuit technology and been silicon-based. In the 1980s, accelerometers emerged as additional high-volume product targets, driven primarily by needs in the automotive industry. Both microactuators and MEMS were born during this decade. Today, visible image sensors are approaching the resolution of photographic film and offer the promise of automatic electronic processing of both video and still images. Infrared imaging has similarly resulted in large area arrays, and recently an uncooled array based on micromachining has been demonstrated and shown to produce excellent results in night-vision applications (Wood, Han, and Kruse 1992). Solid-state pressure sensors have been demonstrated over a broad range of applications, from ultrasensitive devices capable of serving as solid-state microphones or capacitive manometers to rugged devices used in electronic transmissions and in the hydraulic control of heavy equipment, spanning at least eight orders of magnitude in pressure. A variety of accelerometers are being merged with on-chip circuitry for high-volume applications (Payne and Dinsmore 1991), and inertial navigation systems based on integrated gyroscopes (Bernstein et al. 1993) are in development in a number of companies. A high-density projection display system based on arrays of electrostatically-driven micromirrors is also in advanced development (Sampsell 1993). Microflowmeters are emerging for industrial process applications, and still other devices are being designed for chemical sensing and for applications in decoding the human genome. Many of these emerging applications are potentially very high in volume and very important to global society.

Table 1.1 lists some of the devices currently in production or in development worldwide. Many of the devices at the top of the columns are currently in production as individual components, although most are evolving upward in sophistication and accuracy. Toward the bottom of the list are more complex systems, including inertial navigation equipment, chromatography systems, mass spectrometers, and chemical sampling/analysis systems. These are in relatively early stages of development, but represent the realization of entire instrumentation systems in miniature, highly-integrated, and potentially low-cost forms. The evolutionary march toward such microinstrumentation systems is expected to continue, both in Japan and in the United States.

While increasingly recognized as important in the implementation of a wide variety of emerging systems, enthusiasm over the realization of sensors, actuators, and MEMS using microelectronic technology must be tempered by the realization that many such devices have been around in various forms for a long time. An example is the gas chromatograph depicted in Figure 1.5. This system integrates a gas sampling/injection system, separation column, temperature control, gas conductivity detection, and associated signal processing on a single chip and was first proposed in 1972 (Wise, Carle, and Donaldson 1972; Terry, Jerman, and Angell 1979). Lack of suitable microvalves was a principal challenge to the realization of this system, but with recent advances in MEMS, such systems may soon be a reality.

Table 1.1
Integrated Sensors and MEMS in Production or Under Development on a Worldwide Basis

Visible Imagers	Linear Microdrives
Infrared Imagers	Microvalves
Tactile (Force) Arrays	Pressure Sensors
Accelerometers	Temperature Sensors
Humidity Sensors	Magnetic Sensors
Ion Concentration Sensors	Plasma Monitors
Ultrasonic Imagers	High-Energy Detectors
Acoustic Sensors	Neural Probes
Scanning Surface Probes	Gas Detectors
Mass Flowmeters	Gas Analysis Systems
Projection Displays	Gyroscopes
Prosthetic Systems	Mass Spectrometers
Microflow Controllers	DNA Analysis Systems
Cell Growth/Sorting Systems	Micropositioning Systems

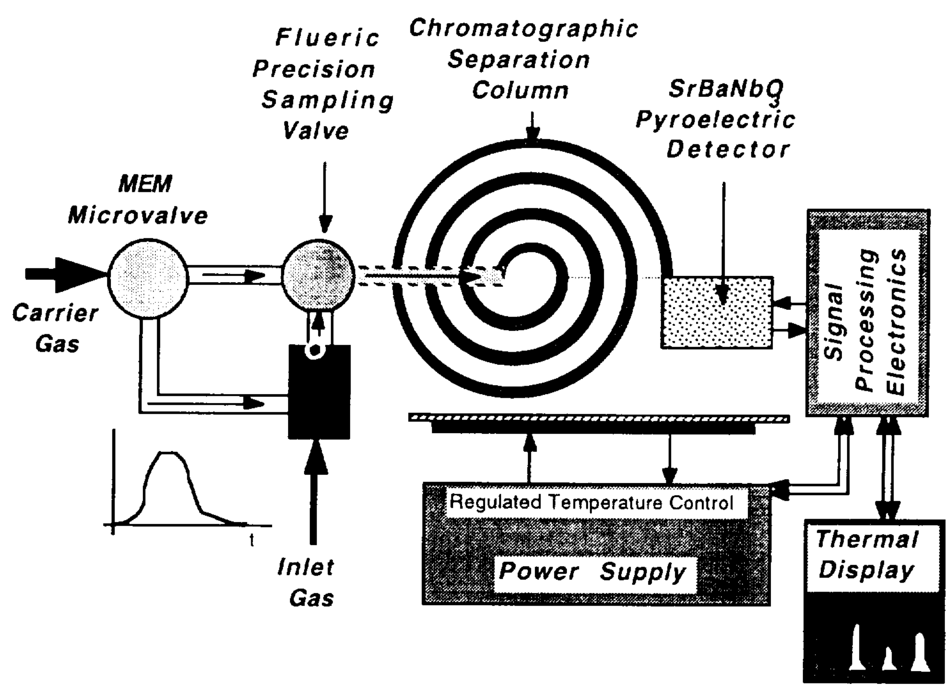


Figure 1.5. Organization of a miniature gas chromatography system, an early example of MEMS. All components except the display and main entry valve were proposed as a single chip in 1972.

The commercialization of integrated sensors, actuators, and MEMS has been relatively slow, and in many areas technology push has been considerably stronger than market pull. This has probably been more true in the United States than in Japan and may be due in part to the more extensive system of university research in the United States, which has produced more research prototypes but also been somewhat less dependent on industry. In some cases, the control system hierarchy into which these devices must work must also change considerably in order to accommodate them, and the general lack of synergy between the sensing and control areas globally has undoubtedly retarded progress. Simply replacing earlier devices with solid-state versions has not fulfilled the potential of this area, and going beyond simple component replacement into integrated microsystems requires interdisciplinary cooperation that is difficult to achieve. Has the technology associated with MEMS now matured to the point where high-volume devices can be realized using batch processes with high yields? If not, when will it do so? Can the specialized processes required for the realization of microelectromechanical microstructures really be successfully merged with circuit processes to form microsystems on a chip? Is this necessary, or will hybrid systems do just as well? Where are the markets for these devices that will demand continuous technology improvements similar to what memory has done for microelectronics? What are the principal high-volume markets that will fuel the sensor/actuator/MEMS industry and significantly benefit society? These are some of the questions considered in this study, where the perceptions and approaches found in Japan are contrasted with those in the United States.

MEMS IN JAPAN

Funding for MEMS-related research has increased substantially worldwide over the past decade. Funding for MEMS in the United States has expanded significantly, and substantial programs are also known to be underway in Europe, particularly in Germany, Switzerland, and the Netherlands. The Japanese national effort under the Japanese Ministry of International Trade and Industry (MITI), begun in 1991 as a ten-year effort funded at about $250 million, has been the most visible effort globally, and better understanding this program was one important focus for the present study as discussed in Chapter 7. Only a relatively small portion of the MITI program (formally titled the Micromachine Technology Project) involves the development of lithography-based MEMS, which are the principal focus for efforts in the United States. A larger portion of the MITI effort is aimed at the development of micromachines, with the thought that many small machines may someday be able to accomplish tasks currently reserved for a much smaller number of their larger predecessors. The goals are both to develop important technologies for MEMS/micromachines and to identify applications to further guide their development. Table 1.2 summarizes some of the important technologies targeted as part of this MITI effort. Many of these technologies, including dry etching and low-temperature wafer bonding, are also targets for development in the United States; however, others, such as microgrinding and electro-discharge machining, have no significant present representation here.

Table 1.2
Some Generic Technologies Chosen as the Focus of the MITI Program in Micromachines

Energy Supplies	Microdynamos, batteries, microwave, photoelectric
Actuators	Electromagnetic, pneumatic, electrostatic, SMA, piezoelectric
Sensors	Ultrasonic, gyros, microsonar, fiber optic imaging
Control	Miniature teleoperators
Dry Processing	Laser-assisted etching, RIE, FIB, ECR
Bonding	Low-temperature wafer bonding, microwelding
Assembly	Micromanipulators
Other Processes	LIGA, EDM, ceramic injection molding, metal molding microgrinding, true micromachining

The MITI program has chosen two target systems to guide its efforts during the first five years. The first is an inspection system for the maintenance of cooling tubes in power plants. This system, described in Chapter 7, is composed of four parts: a mother ship capable of traversing the 10 mm main cooling tubes; a wireless microcapsule (no more than 2 mm in diameter) capable of navigating through smaller cooling tubes; a wireless inspection module capable of making detailed analyses of cracks or occlusions in the smaller tubes; and a 2.5 mm OD operation module intended to repair any defects found. A second vehicle is a multilumen active biomedical catheter containing tools for imaging, position control, and microsurgery. The targeted size is in the range of a few millimeters OD. A third project under consideration deals with the development of micromachines to reduce energy consumption in manufacturing and focuses on reducing the size of conventional clean rooms for commercial VLSI wafer fabrication. All of these projects demonstrate the ability of the Japanese to set long-range goals and marshall resources from numerous companies to work cooperatively toward them. They also demonstrate an important approach to the development of a new field such as MEMS, where many of the eventual applications are not yet clear. The Japanese readily admit that none of the projects described above may actually be realized, at least not as currently envisioned. They are merely vehicles for focusing the research. But they involve most of the technologies that are thought to be needed for a broad range of the perceived applications, and it is felt that in the process of working on these systems many useful technologies and products will be spun off. They are an example of the old adage for successful research, "If you don't know exactly what to do, do something!", and are an effective way of focusing resources in an emerging area.

Japanese programs have been significant in the development of sensors, actuators, and MEMS in the past through programs at a number of universities and companies, and the leadership of Japanese industry in consumer products puts them in an excellent position to benefit from MEMS technology. Indeed, the industrial resources being focused on lithography-based sensor development and to some extent on MEMS in Japan are significantly greater than the MITI micromachine program. As in the United States and Europe, however, the total amount being spent on MEMS-related development in Japan is difficult to estimate and remains unknown.

METHODOLOGY FOR THIS STUDY

In conducting this study, the challenges facing the development of MEMS were divided into the following areas:

- Advanced materials and process technology
- Sensors and sensing microstructures
- Microactuators and actuation mechanisms
- Sensor-circuit integration and system partitioning
- Advanced packaging, microassembly, and testing technologies
- MEMS design techniques, applications, and infrastructure

A total of 74 specific questions covering these six areas were prepared and mailed to 23 organizations (5 government agencies or laboratories, 6 university laboratories, and 12 industrial sites) that were known to be working in MEMS-related areas and were felt to represent a cross-section of activity in Japan. The questions were intended to raise important issues as a framework for discussions. In some cases, they were addressed specifically in the ensuing site visits in Japan, while in other cases the answers became apparent through the formal and informal discussions which occurred on-site. The panel spent one week in Japan visiting these 23 sites. The questions, sites visited, and site reports are all included as appendices to this report. The body of the report thus consists of six sections dealing with Japanese efforts in the areas noted above.

SUMMARY

Microelectromechanical systems have the potential to leverage microelectronics into important additional areas that could be revolutionized by low-cost electronic signal processing, computing, and control. These microsystems could have a profound effect on society but will require synergy among many different disciplines that may be slow in coming. Global leadership and cooperation will be absolutely required if we are to realize the benefits of MEMS in a timely way. This report examines the recent activities in Japan in tackling these problems and contrasts them with U.S. approaches and perceptions. Only by understanding the potential of this emerging field and by working together to overcome its challenges will we ensure the early utilization of MEMS to benefit mankind.

REFERENCES

Bernstein, J., S.T. Cho, A.T. King, A. Koutrpenis, P. Maciel, and M. Weinberg. 1993. "A Micromachined Comb-Drive Tuning Fork Rate Gyroscope." In *Digest IEEE Microelectromechanical Systems Workshop.* Pp. 143-148.

Gabriel, K.J. 1993. "A MEMS Technology Update." In *SEMICON/East Workshop on Microelectromechanical Systems: An Emerging Market for the IC Industry.*

Guckel, H., K.J. Skrobis, T.R. Christenson, J. Klein, S. Han, B. Choi, and B.G. Lovell. 1991. "Fabrication of Assembled Micromechanical Components via Deep X-Ray Lithography." In *Digest IEEE Workshop on MicroElectroMechanical Systems.* Pp. 74-79.

Payne, R.S., and K.A. Dinsmore. 1991. "Surface Micromachined Accelerometer: A Technology Update." In *Digest SAE Meeting (Detroit).* Pp. 127-135.

Petersen, K.E. 1982. "Silicon as a Mechanical Material." *Proc. IEEE.* May: 420-457.

Sampsell, J.B. 1993. "The Digital Micromirror Device and its Application to Projection Displays." In *Digest Int. Conf. on Solid-State Sensors and Actuators.* Pp. 24-27.

SEMICON Daily News. 1993. TPI Publications. SEMICON/East. 20 October: 1, 4, 8.

Terry, S.C., J.H. Jerman, and J.B. Angell. 1979. "A Gas Chromatographic Air Analyzer Fabricated on a Silicon Wafer." *IEEE Trans. Electron Devices.* 26, December: 1880-1886.

Wise, K.D. 1991. "Integrated Microelectromechanical Systems: A Perspective on MEMS in the 90s." In *Proc. IEEE MicroElectroMechanical Systems Workshop.* Pp. 33-38.

Wise, K.D., and K. Najafi. 1991. "Microfabrication Techniques for Integrated Sensors and Microsystems." *Science.* 254, 29 November: 1335-1342.

Wise, K.D., G.C. Carle, and R.W. Donaldson. 1972. "Microminiature Gas Chromatograph." Patent Disclosure. Stanford University/NASA, June 1972.

Wood, R.A., C.J. Han, and P.W. Kruse. 1992. "Integrated Uncooled Infrared Detector Imaging Arrays." In *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 132-135.

CHAPTER 2

MATERIALS AND PROCESSES

Henry Guckel

INTRODUCTION

The topic for this particular report section involves a large if not infinite body of material. This implies at least two major problems: not all relevant topics will be covered and there are great difficulties in organizing the material in some sort of logical fashion. For the first problem there is no answer except perhaps an apology and the assurance that omissions are unintentional. The second difficulty is solved by organizing the material along processing techniques: conventional, lithographic, and atomically precise.

CONVENTIONAL PROCESSING

Japanese industry, as exemplified by companies such as Nippondenso, Hitachi, Mitsubishi Electric Company (MELCO), and many others, maintains R&D programs that improve precision and manufacturability in large as well as small devices. This is particularly true in fields such as low temperature bonding. Hitachi uses high vacuum sputter cleaning to produce oxide-free bonding surfaces prior to vacuum bonding via applied pressure and temperature. The company reports good results for many metal systems with areas ranging from several square centimeters to fractions of a square centimeter. Mitsubishi Electric is also active is this area, and reports silicon to silicon bonding and silicon to silver bonding at room temperature without applied pressure after sputter etching in 10^{-9} Torr vacuum. A second area, not reflected in the site reports, is precision polishing. At Nippondenso, improved polishing techniques have been used to produce thin piezoelectric ceramics for use in stacked actuators for active suspensions. Results from these polishing techniques are reflected in sensor manufacturing, where precision polishing is of major concern, as demonstrated by the devices that Lucas-Nova Sensor, Inc., a U.S.-based company, markets.

A third area that fits well into the conventional and lithographic processing world is that of electro-discharge machining (EDM). This area has received long-term attention in Japan. The results are not only interesting devices but also the marketing of equipment that can perform this function. Thus, Matsushita makes and sells EDM machines that can be used for metals and semiconductors, and are capable of holding tolerances to 0.1 μm with minimum dimensions of 5 μm.

This type of tool and other precision tools are used by Seiko Instruments, Incorporated (SII) to make a variety of commercially available millimotors. Alternating current (AC), direct current (DC), and ultrasonic actuation are used. A three-phase stepping motor with 60° stepping angle, with speeds up to 13,000 rpm and output torques of 1.2×10^{-6} Newton-meter, can be purchased for roughly $1,000. Its length is 5 mm and its diameter is 2.8 mm; its 0.5 mm output shaft can be coupled to a 23:1 reduction gear box which is also available.

This motor and gear box are simply examples of several similar devices that SII produces and markets. The design of these structures is obviously labor intensive, and profits from a mechanical CAE/CAD/CAM system that SII has developed and is using. This multiple-option system is also marketed by SII.

Precision injection molding also fits into the conventional and lithographic processing category. Research in this area is supported by private companies and national laboratories. The view expressed by representatives of the Mechanical Engineering Laboratory (MEL) -- that polymer injection molding is already under control -- is somewhat surprising. Precision injection molding for metals and ceramics are high priority R&D projects.

Industrial attitudes towards lithographic processing also profit from the willingness to adapt available processes and processing tools to the task at hand. This is particularly true in magnetics. Thus, Mitsubishi Electric experiments with sputtered films of Sendust (85% Fe, 9.5% Si, 5.5% Al), a material that is used extensively in magnetic recording. Permalloys, typically 80% Ni and 20% Fe, play a major role in read/write heads and have been studied extensively for several decades. MELCO uses sputtered and electroplated films for magnetic micromechanical devices. NTT adapts its skill and knowledge in permalloys to produce optimized relay springs from 2-micron thick sputtered alloy films.

A willingness to invest time and energy in process tool development is exemplified by Hitachi. The company uses its silicon machining skill (which originated in ultrasonics, particularly lens production) to produce large half-spheres, about 4 cm in diameter, from a silicon ingot. These structures, which contain all possible silicon crystallographic directions, are etched in potassium hydroxide etches to produce etch rate versus orientation data for several etch conditions. The data are used in a computer simulation tool to predict etched geometries as a function of etch time. Two-dimensional simulations are fully functional, and three-dimensional predictions will be in the near future. The tool is being applied to silicon sensors and reflects itself in particular in accelerometer development for automotive applications at Hitachi (Wise 1994).

LITHOGRAPHIC PROCESSING

Perhaps one of the more unusual processing sequences in micromechanics is the selective epitaxial silicon deposition and electrochemical etch technique that Yokogawa Electric Corporation uses to produce its resonating force transducer. This process, which Yokogawa has worked on for several years, is responsible for the resonating pressure transducer that Yokogawa markets. Twenty-thousand units were sold in 1992. Specifications of 0.1 percent accuracy with 26 inch wafer devices with 100:1 turndowns at the same accuracy reflect the high quality of the device. Discussions at Yokogawa about the choice of this particular processing tool for this type of sensor indicate that major issues are known material constants and behavior. The device is formed from single crystal silicon. This concern is shared by Toyota Research, where materials research into films such as silicon carbide is justified with comments on the possible unsatisfactory long-term behavior of polysilicon when used as a sensor construction material. The reader is cautioned: this may or may not be so. There are no hard published data available. The point here is simply that reliability data for polysilicon and many other materials are badly needed to avoid unpleasant surprises in the future. In a sense, possible problems are avoided by restricting material choices to bulk silicon.

One of the major issues in micromechanical processing tools for actuators involves the ability to construct high aspect ratio structures. The best tool for this involves X-ray assisted or LIGA-like processing, which has now achieved structural heights of 1 cm with minimal run-out (Guckel et al. 1994). This processing tool depends on access to a bright X-ray source: an electron storage ring or synchrotron. Since machines of this type are typically large and always expensive, they are normally shared by many users. Access may therefore mean off-site processing. Reaction to X-ray assisted processing falls into two categories: acceptance via participation or avoidance via alternative approaches to high aspect ratio processing. Both situations occur in the United States and in Japan.

Interest in X-ray assisted processing in Japan is high. Nearly every facility that was included in the site visits expressed an interest. Two sites, SORTEC, a national synchrotron facility, and Mitsubishi Electric, with its own superconducting synchrotron, have or are constructing beam lines for deep X-ray lithography. Seiko Instruments has worked with the German company Microparts to produce and test microgears, and indicated continued interest during the site visit. However, there are also problems. Concern was expressed over the lead that Europe and the United States have in this area. The patent issue in particular was mentioned, and the cost of the process was criticized at Toyota. These remarks in turn are balanced by the questions that one senior Japanese researcher posed: Can Japan really afford not to participate?

Technical concerns that the Japanese must consider start with the source. Deep X-ray lithography requires photon energies above 3,000 eV. VLSI X-ray lithography, in which there are significant efforts in Japan, typically uses 200 eV photons. Since the new sources at Mitsubishi Electric and Sumitomo are aimed at VLSI lithography, their outputs are too soft for deep X-ray lithography. It is unclear but doubtful that these compact machines can be furnished with insertion devices to shift their outputs to shorter wavelengths and larger powers. SORTEC, a warm ring at 1 GeV, could be modified with a wigler to make it a very acceptable photon source for X-ray assisted processing. The Photon Factory in Tsukuba has the required characteristics. However, this machine belongs to the Ministry of Education, which makes it a doubtful candidate for a manufacturing effort (Clemens and Hill 1991).

The source issue has taken a somewhat unusual turn in Japan. Representatives of the Fujita Corporation, a large Japanese construction company, visited Madison about one year ago. They indicated that they were interested in exploring the possibility of constructing a high energy synchrotron in Chiba and operating it at a profit with multiple users. The project, which the Fujita Corporation called the Nano Hana Project, is still active and viewed with mild pessimism by some Japanese researchers.

Support for X-ray assisted processing requires thick photoresists and the processing technology that makes them useful. There are no indications that X-ray sensitive polymers for this type of work are of major concern in Japan. However, the results of high aspect ratio photoresist work at SORTEC, which produces strain induced mechanical failures in high resolution patterns with photoresist thicknesses of 5 microns, are applicable to thick photoresists with larger feature sizes and thicknesses, but similar aspect ratios. The SORTEC work is based on a German photoresist that is manufactured by Hoechst.

Electroplating, a major problem for LIGA-like processing, is being used at Professor H. Fujita's laboratory at the University of Tokyo with conventional thick photoresists to produce wobble motors and other actuators (Hirano, Furuhata, and Fujita 1993). There are other activities in Japan that deal with conventional electroplating issues, but there are no known activities that deal with the very special challenges that thick, high aspect ratio, LIGA-like photoresist technologies offer.

Processing procedures that attempt to duplicate results from X-ray assisted processing are normally called "high aspect ratio machining," or HARM. In the United States, emphasis in HARM centers on thick photosensitive polyimide technology as practiced by M. Allen of Georgia Tech. In Japan, Professor Masayoshi Esashi of Tohoku University and NTT researchers have reported on plasma etching of fully imidized polyimide to achieve vertical flanks with structural heights in the range of a few hundred microns (Murakami et al. 1993). Professor Esashi's group uses a nickel mask during plasma etching. The etch gas is oxygen. The reactor uses a cooled substrate support that can be used to produce substrate temperatures as low as 77°K during etching. The plasma energy in the parallel plate reactor is reduced by coupling a static magnetic field from external permanent magnets into the discharge. Very high gas flow rates typify the etching procedure. The NTT work is similar to the Tohoku procedures, but utilizes a more automated reactor (Furuya et al. 1993). Both research groups report very nice HARM results that can be used to produce interesting actuators such as the distributed electromechanical actuator, or DEMA, which has been described by Professor Esashi (Yamaguchi et al. 1993).

Toyota research laboratory also reports that it has a HARM process. The details of the Toyota process have not been disclosed.

ATOMICALLY PRECISE PROCESSING

The author had the privilege of visiting Professor Esashi's laboratory at Tohoku University several years ago and again during this JTEC study. The changes at Tohoku University are remarkable. There is a new clean room and lots of sophisticated equipment that one needs for atomically precise rather than lithographic processing. The fact that Professor Esashi is an Associate Director of the Semiconductor Research Institute and has access to work in atomic and molecular epitaxy that originated with Professor Nishizawa, currently the President of Tohoku University, hints at a shift in emphasis towards nanomechanics. This change makes sense at Tohoku University. It also makes sense from a national perspective if the attitude is that Japan is behind in silicon micromechanics and in X-ray assisted processing. Work on precision gas valves that is in progress at several companies would yield improved control over gas sources for sophisticated epitaxial growth techniques, an important nanomechanical technology. A similar comment applies to several activities in Japan on miniature focused ion beam sources, which fit well into the concept of nano- rather than micromechanics. These devices, which are viewed as important tools for miniature, energy-efficient factories, can only support nanospace.

REFERENCES

Clemens, J., and R. Hill, ed. 1991. *JTEC Panel Report on X-ray Lithography in Japan.* PB92-100205, Springfield, VA:NTIS.

Furuya, A., F. Shimokawa, T. Matsuura, and R. Sawada. 1993. "Micro-grid Fabrication of Fluorinated Polyimide by Using Controlled Reactive Ion Etching (MC-RIE)." In *Proc. of IEEE-MEMS Conference.* Pp. 59-64.

Guckel, H., K.J. Skrobis, T.R. Christenson, and J. Klein. 1994. "Micromechanics for Actuators via Deep X-ray Lithography." Paper presented at SPIE's 1994 Symposium on Microlithography. Paper 2194-09. February. San Jose, CA.

Hirano, T., T. Furuhata, and H. Fujita. 1993. "Dry Released Nickel Micromotors and their Frictional Characteristics." In *Proceedings of the 7th International Conference on Solid-State Sensors and Actuators.* Pp. 80-83.

Murakami, K., Y. Wakabayashi, K. Minami, and M. Esashi. 1993. "Cryogenic Dry Etching for High Aspect Ratio Microstructures." In *Proceedings of IEEE-MEMS Conference.* Pp. 65-70.

Wise, K.D. 1994. "Sensor-Circuit Integration and System Partitioning." In *JTEC Panel Report on Microelectromechanical Systems in Japan.* K. Wise, ed. Springfield, VA:NTIS.

Yamaguchi, M., S. Kawamura, K. Minami, and M. Esashi. 1993. "Distributed Electrostatic Microactuator." In *Proceedings of IEEE-MEMS Conference.*

CHAPTER 3

MEMS - BASED SENSORS

G. Benjamin Hocker

INTRODUCTION

Micromachining technology began to develop rapidly over fifteen years ago, using materials and processes developed for the integrated circuit industry to form miniature structures in silicon and related materials for purposes other than electronic devices. The fabrication of miniature solid state sensors has long been the main thrust of micromachining technology. Much of what is today termed "MEMS" is in some ways only an evolution and expansion of this technology. Improvements possible with MEMS technology involve the expanded range of materials and processes that can be employed, the precise dimensional scale and mechanical complexity that can be achieved in devices, and expanded capabilities for electronic integration. For commercial products, sensors are still the major near-term application thrust of MEMS both in the United States and Japan.

As the term "microelectromechanical systems" suggests, MEMS technology relates most directly and has the greatest impact on sensors for mechanical variables. In contrast, most of the solid state sensor developments for magnetic sensors, chemical sensors, gas sensors, and biosensors do not use significant microstructures or electronic integration, and so do not fall within the definitions of MEMS concepts and technology. These developments were not covered in the selection of Japanese laboratories visited or in this study, and are not discussed in detail here. Additionally, there is a vast array of sensor technology outside the realm of miniature, solid-state devices that is not addressed by this study.

This chapter examines specific MEMS-based sensor technology developments in Japan, both in industry and universities. These are then compared with sensor developments in the United States.

SENSOR DEVELOPMENT IN JAPAN

Industry

Much of the work on MEMS-related technology that the JTEC panel saw in Japanese industrial research laboratories focused on sensor applications. This is undoubtedly due to the long history of microsensor technology development, and to the relatively near term nature of commercial sensor products compared to the more speculative nature of many microactuator and micromachine applications. Like most of their U.S. counterparts, MEMS sensor technology developments in Japanese industry concentrate on Si-based technology, including use of integrated electronics.

This section will focus on companies visited by the JTEC panel. This group does not include all sensor research in Japan, but is believed to represent MEMS sensor R&D in Japanese industry. Because of the proprietary nature of most industrial research, the work discussed by the Japanese laboratories was mostly that which had been previously presented or published. There is doubtless a great deal more research underway that is not open for discussion. In some cases, speculation can be made as to present research activities not revealed.

Toyota Central Research and Development Laboratory. This large laboratory has a long history of significant sensor R&D. There are many present and future applications for sensors in automobiles, with requirements for low cost, high volume production, and high reliability. Accordingly, the focus of MEMS research at the Toyota Central R&D Laboratory is almost entirely on silicon microsensors, including an emphasis on monolithic integration of sensors with electronics. This represents a relatively large effort at Toyota, with about ten researchers dedicated to silicon microsensors plus significant support from groups in materials, IC design and processing. A very capable CMOS prototype line is in place at the laboratory, and is used for development of integrated sensors.

Development of physical sensors based on bulk silicon micromachining began many years ago at Toyota; they are reportedly in production. Now the R&D emphasis is on sensors built using surface micromachining of thin film materials such as polysilicon and silicon nitride, along with a major thrust on integration of sensors with CMOS electronics.

Much of the silicon sensor device research at Toyota has been on pressure sensors, critical devices for a variety of control applications in automobiles. This can even involve the very difficult job of sensing pressures within the engine combustion chamber (Morikawa et al. 1993). Toyota's pressure sensor work is generally innovative, and equivalent to similar efforts in the United States. An earlier example of a fully integrated pressure sensor is given in Yamashita et al. (1989). A more recent example of an innovative pressure sensor is the recent surface micromachined microdiaphragm device shown in Figure 3.1 (Shimaoka et al. 1993). This device uses a silicon nitride diaphragm with polysilicon piezoresistors, resulting in a small area diaphragm only 100 μm diameter by 1.6 μm thick. Such small devices can be efficiently combined with electronics for low cost integrated sensors. The ease of integration with electronics is illustrated by an earlier version of the microdiaphragm pressure sensor that was integrated into a 32 x 32 (1K)-element array shown in Figure 3.2 (Sugiyama et al. 1990). This large sensor array is complete with CMOS addressing and readout circuitry, and can be used for tactile sensing.

Another pressure sensor, developed in conjunction with researchers at Toyoda Machine Works and Tohoku University, is shown in Figure 3.3 (Nagata et al. 1992a). This is a bulk micromachined capacitive device, formed by bonding silicon and glass wafers, complete with some CMOS electronic circuitry. It has a 2 mm square diaphragm, much larger than the previous device. The device is built for a low pressure range of 0 to 20 Pa, and can have high overpressure protection. It is combined with a digital electronic chip for compensation and digital output. Using a similar concept and structure, many of the same authors have reported a capacitive accelerometer (Nagata et al. 1992b), another useful automotive sensor for air bag deployment and active suspension control.

Other silicon microsensor work at Toyota has involved uncooled infrared (IR) sensors and arrays utilizing the thermal isolation properties of silicon microstructures. One type detects the temperature rise due to incident IR radiation through a polysilicon pn junction diode (Tanaka et al. 1992), carried out with researchers from Hamamatsu. Another uses a thin film polyvinylidene fluoride (PVDF) pyroelectric (Asahi et al. 1993), as shown in Figure 3.4. IR detection and imaging is an excellent application of the features and advantages of microstructures. These microstructures have high thermal isolation and low heat capacity, and so undergo detectable temperature changes from low levels of incident IR radiation.

In addition to the work on silicon microsensors, there is a similar-sized group working on gas sensors, typically for exhaust emission control. The emphasis is on thin film materials, such as ZnO and SnO. This technology does not use silicon or significant micromachining technology, so is not in the realm of MEMS.

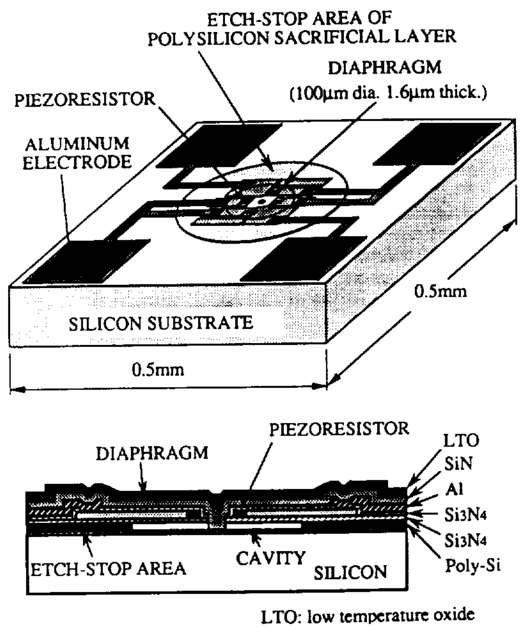


Figure 3.1. Schematic and cross-sectional view of Toyota's surface micromachined piezoresistive microdiaphragm pressure sensor (Shimaoka et al. 1993).

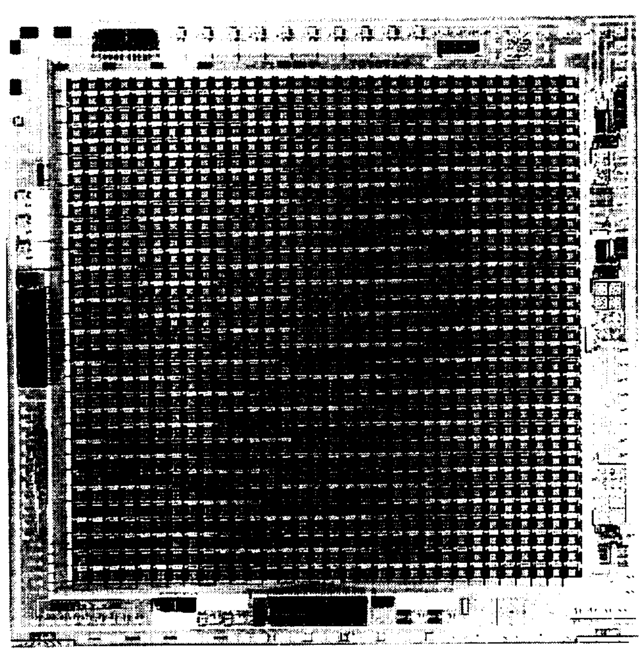
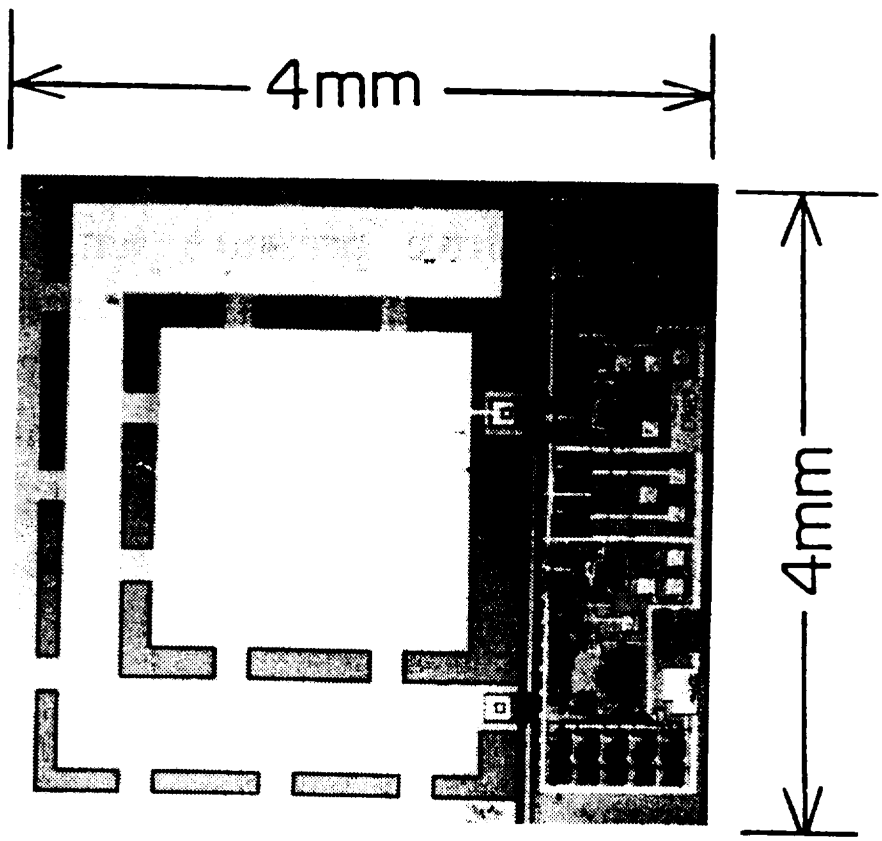
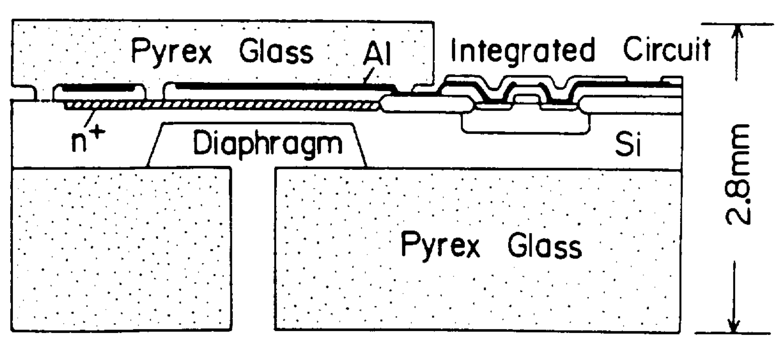


Figure 3.2. Toyota 32 x 32 (1K)-element piezoresistive pressure/tactile sensor array (Sugiyama et al. 1990).

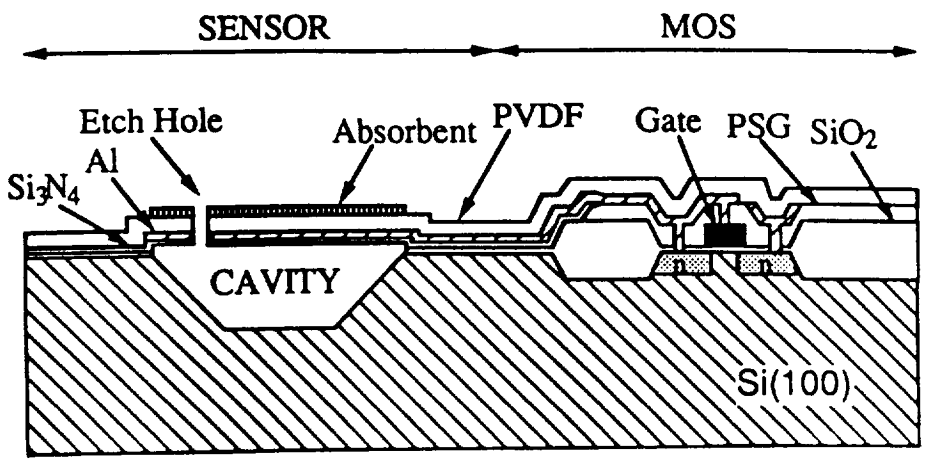


(a)

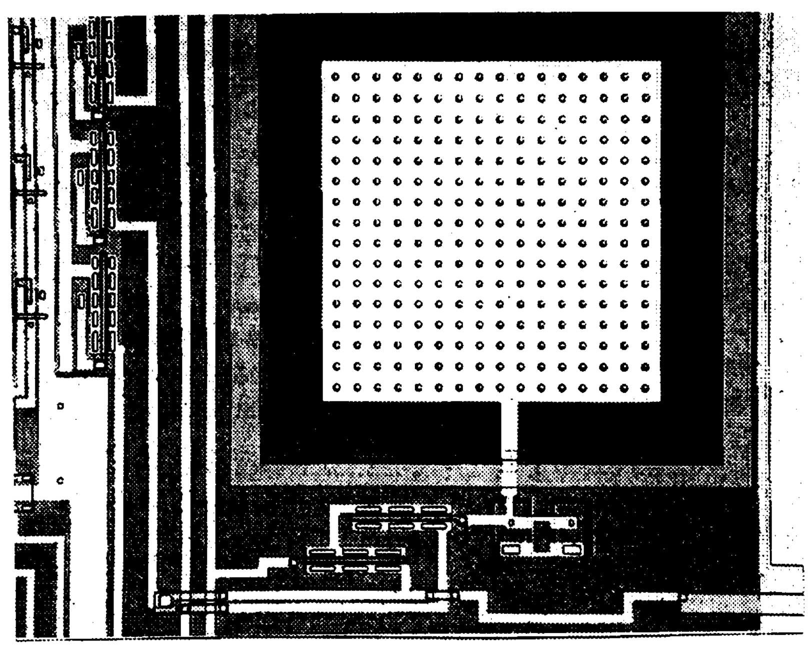


(b)

Figure 3.3. Photograph (a) and cross-sectional structure (b) of Toyota capacitive pressure sensor with CMOS electronics (Nagata et al. 1992a).



(a)



(b)

Figure 3.4. Toyota's pyroelectric IR sensor (Asahi et al. 1993): schematic cross-sectional structure (a) and photograph of the sensor chip before forming an absorbent (b).

Nippondenso Research Laboratories. Since Nippondenso is a member of the Toyota Group of companies and a major automotive component supplier, its focus on sensors using MEMS technology is similar to that of Toyota Central R&D Laboratory. Sensors were stated as Nippondenso's first target for MEMS technology, and the laboratories are extensively developing suitable process technology. Bulk micromachined sensors are in production, and efforts are under way on sensors using poly-Si surface micromachining and wafer bonding. The laboratories' efforts are large, with about thirty people working on micromachining and about ten on the national (MITI) Micromachine Technology Project.

Specific developments shown include an integrated pressure sensor for engine control and an air bag crash sensor/accelerometer. The pressure sensor is a rather standard piezoresistive sensor with a square anisotropically-etched diaphragm but with considerable integrated electronics on a 2.8 mm square chip. The crash sensor is based on a bulk micromachined cantilever beam with piezoresistive sensors, also with extensive integrated electronics. The chip size is 8.3 x 3.6 mm, and is packaged in silicone oil for damping. No detailed information on these devices was available, and no published references have been found. It is most likely that these devices are in or near production. An example of recent work published by Nippondenso is a highly integrated sensor chip with multiple diaphragm pressure sensors and temperature sensors, shown in Figure 3.5 (Fujii, Gotoh, and Kuroyanagi 1992). This device includes use of wafer bonding for cavity and port fabrication, as well as thin film silicon nitride diaphragms similar to the Toyota work described above.

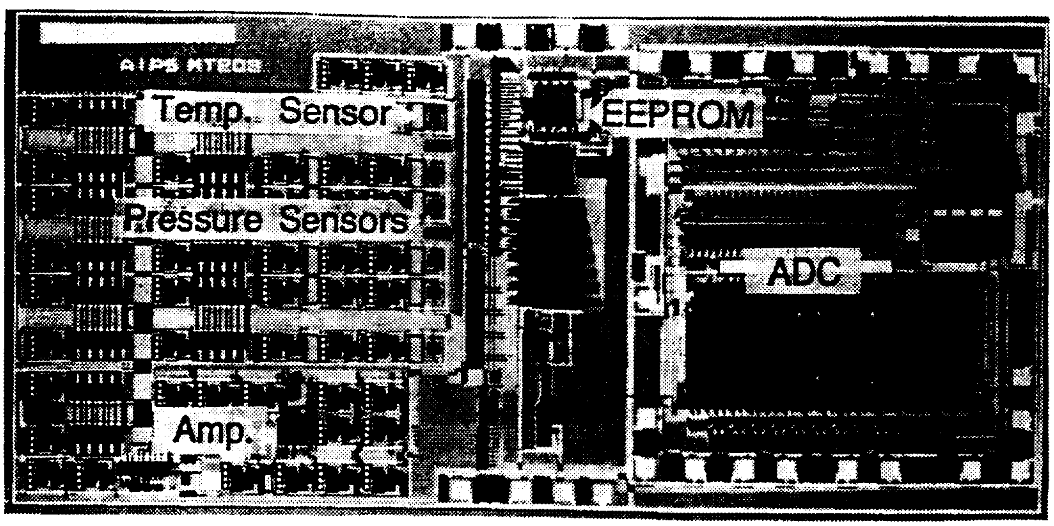


Figure 3.5. Top view of the Nippondenso integrated pressure and temperature sensor chip (Fujii, Gotoh, and Kuroyanagi 1992).

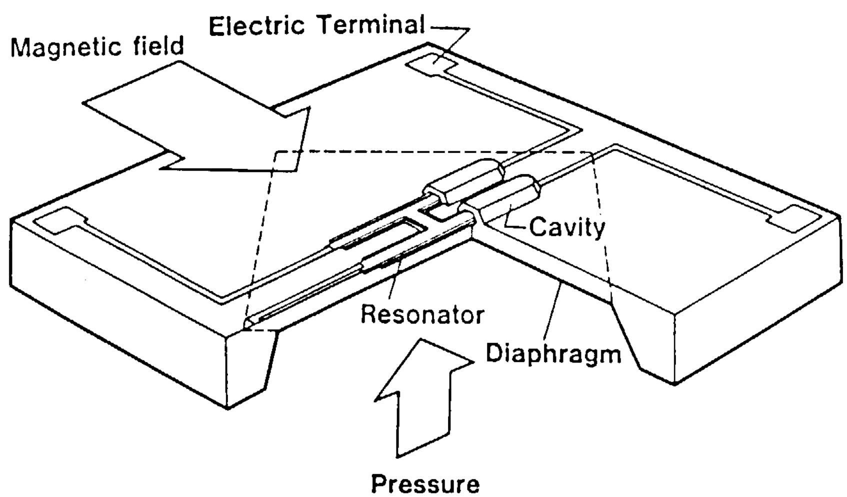
Another interesting device mentioned briefly was a yaw rate sensor (gyro), apparently for automobile steering/braking/suspension control. This sensor was not based on silicon, but was a vibrating metal tuning fork with piezoelectric drive. Similar devices have been demonstrated at several laboratories worldwide, often made from piezoelectric quartz and aimed at low performance inertial systems on missiles, for example, but are relatively expensive. The Nippondenso approach may allow lower-cost fabrication while still providing useful sensitivity for automobile control.

Nippondenso is also working on a variety of wafer bonding technologies, as are U.S. industrial laboratories developing advanced sensors. An earlier paper described an integrated pressure sensor with dielectric isolation, fabricated by silicon wafer bonding (Fujii et al. 1990). Wafer bonding technology is extremely useful for both sensor fabrication and sensor packaging at the wafer level, which is the likely focus of Nippondenso's work.

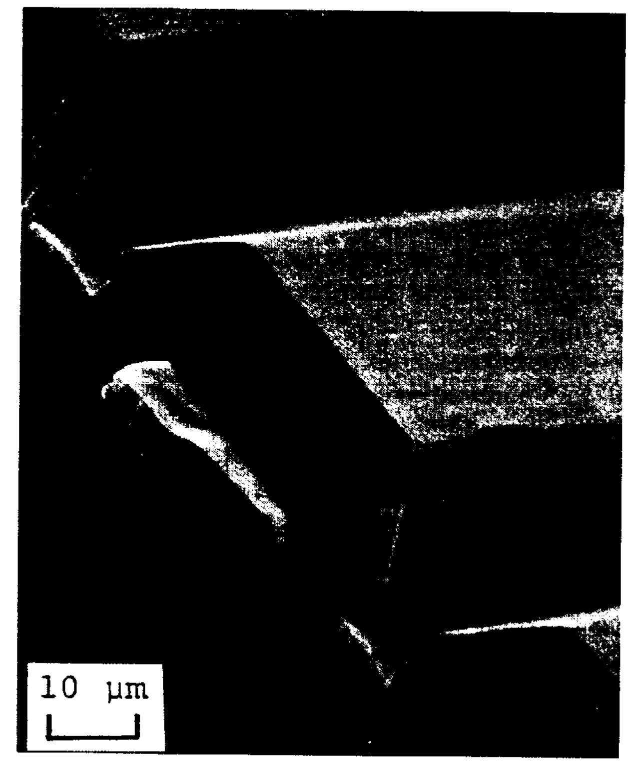
Nippondenso's work on the MITI micromachine project involves sensors and microactuators, but is said to use materials other than silicon, such as piezoelectrics.

Yokogawa Electric Corporation. In contrast to Toyota and Nippondenso, whose businesses require high volumes of low-cost sensors of moderate performance, Yokogawa's industrial sensing and control business is aimed at high performance sensors that can sell for higher prices in modest volumes. Pressure sensing is the dominant industrial application addressed by MEMS sensors. For Yokogawa's pressure sensing applications, silicon sensor technology is found to be advantageous because of its high performance capabilities.

The recently introduced Yokogawa DPharp industrial pressure transmitter is a high-performance industrial instrument which derives its performance from a unique, state-of-the-art silicon sensor chip. This chip incorporates an electromagnetically driven resonant beam sealed in a vacuum shell, integrated onto a standard silicon pressure sensor diaphragm. It is shown in Figure 3.6 (Ikeda et al. 1988, 1990a, 1990b). Driven into resonance by closed-loop feedback electronic circuitry, the beam is stressed as the diaphragm deflects under pressure, with the resulting change in resonant frequency serving as a highly sensitive measure of pressure. As implemented, there are two such beams on the diaphragm, one in the center and the other at an edge, used differentially. The device offers wide dynamic range, high sensitivity, and high stability, along with a frequency output for easy interface to digital compensation circuitry. The chip fabrication is challenging, comprising four sequential selective epitaxial growth and critical selective etching steps, and the sensor package is extremely complex. It is expensive to produce. It is, nonetheless, an excellent example of the power of silicon microfabrication technology, and represents a major technical achievement.



(a)



(b)

Figure 3.6. Yokogawa resonant microbeam pressure sensor (Ikeda et al. 1990b): construction of the sensor (a) and cross-sectional SEM photograph of the resonator (b).

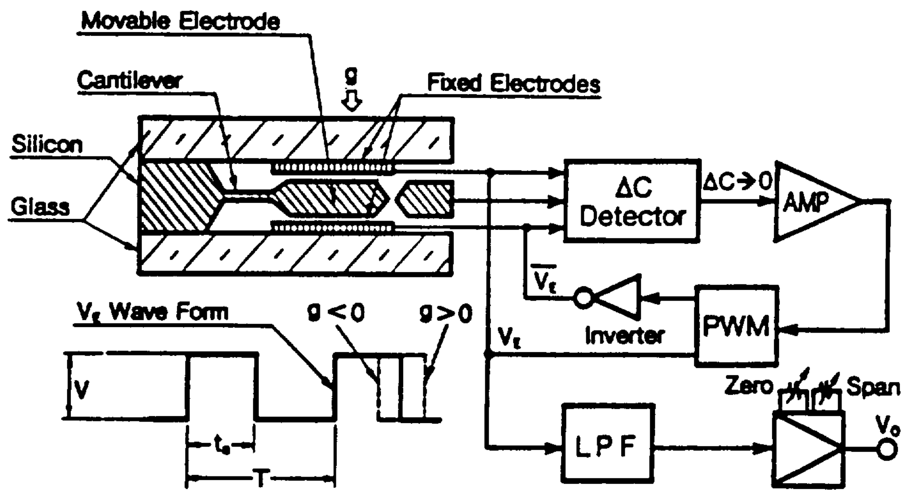
The DPharp product is a smart pressure transmitter used to instrument industrial processes. It includes the packaged sensor chip, the associated analog drive/sense circuitry, and digital compensation for linearization, temperature compensation, diagnostics, and communication (Saito et al. 1992). This smart transmitter approach is similar to those offered by Honeywell, Rosemount, and others in the United States. The performance of the Yokogawa transmitter product is excellent, with accuracy of about ± 0.01% over a wide temperature and pressure range, equal to the best of such transmitters on the market.

Others. Many other Japanese industrial laboratories appear to be developing MEMS-based sensors, primarily in silicon technology. While Matsushita Research Institute, visited by the JTEC panel, carries out little sensor development, it was stated that the Matsushita Living System Research Laboratory has extensive sensor developments under way. The thrust of that laboratory is consumer products, such as appliances, which are using sensors increasingly. Matsushita has a goal of replacing many conventional sensors with semiconductor-based devices; the major reasons are cost and reliability improvements.

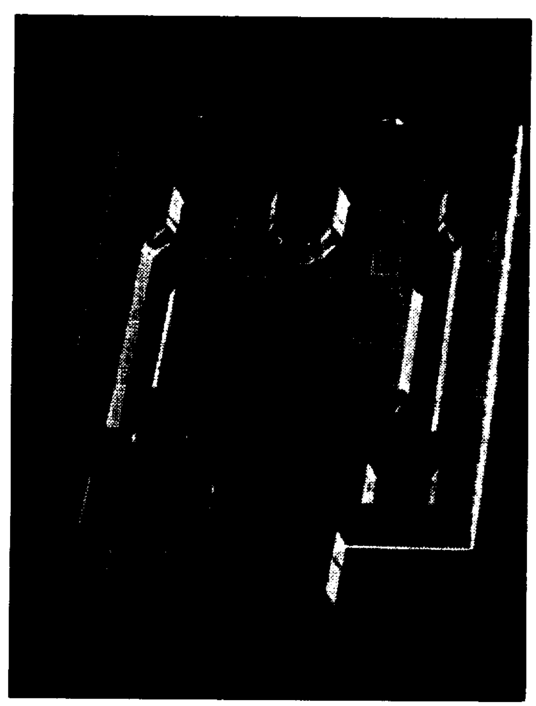
Hitachi representatives have described the development of a closed-loop silicon accelerometer (Tsuchitani et al. 1991). It is intended for automotive systems, and is scheduled for release as a product in 1994. This device, shown in Figure 3.7, requires sophisticated double-sided etching to achieve the desired symmetrical structure that eliminates cross-axis sensitivity (Koide et al. 1992). The 3.2 x 5 mm silicon chip is bonded between glass plates to form a differential capacitor, and mounted with hybrid electronics.

At several of the Japanese companies visited, sensor activities were not discussed in any detail, although they are probably taking place: Seiko makes a number of solid state sensors, using both silicon and quartz piezoelectric technology, but specifics were not described. Omron indicated an emphasis on silicon sensors, including bulk and surface micromachining along with electronic integration, but no specifics were given. Sensor developments also were not covered at Canon or Olympus. At most of these locations, the conversations focused on microactuators and micromachines, rather than sensors.

While not visited by the JTEC panel, a number of other Japanese companies have MEMS sensor technology under development or even in production. Examples include: (1) Fujikura Ltd. has for some years sold piezoresistive silicon pressure sensors as components in the United States and Japan for commercial (including automotive) applications. Recent reports include an integrated pressure sensor with an anisotropically etched diaphragm, bipolar analog signal conditioning electronics, and voltage output (Itoh, Adachi, and Hashimoto 1992). Fujikura is also offering a silicon piezoresistive accelerometer product. (2) Fuji Electric Company has reported a somewhat similar integrated pressure sensor with isotropically etched diaphragm and bipolar electronics, achieving good performance of ±1% over -50 to



(a)



(b)

Figure 3.7. Hitachi closed loop capacitive accelerometer (Koide et al. 1992): schematic (a) and SEM photograph (b).

+175°C (Kato et al. 1991). These devices seem comparable to integrated pressure sensors recently available in the United States. (3) Nissan Motor Company Central Engineering Laboratories has reported an integrated accelerometer, shown in Figure 3.8, employing a bulk micromachined cantilever, piezoresistive readout, and bipolar electronics for amplification and temperature compensation (Muro et al. 1992).

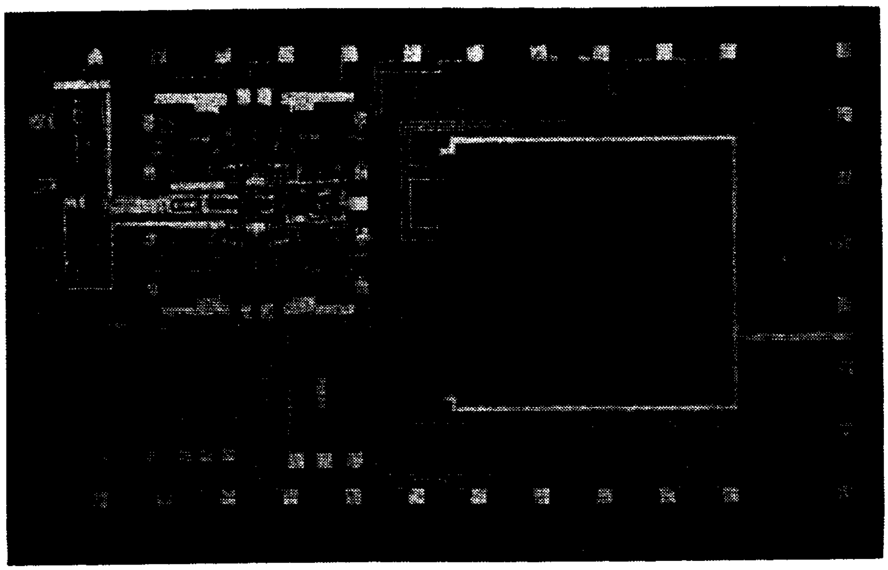


Figure 3.8. Nissan integrated silicon accelerometer (Muro et al. 1992).

Universities

Unlike Japanese industrial laboratories, most of the Japanese universities visited do not have large MEMS sensor research efforts. Instead, university research is on long-term, innovative approaches to microactuators, micromachines, and microrobots. Carrying out leading edge sensors research at the level of the best United States and European universities requires strong capabilities in materials and processing, including electronic circuit integration. The facilities, technology capabilities, and critical mass needed to do are not present at most Japanese universities. Some niche sensor research is carried out in these and other universities within the technology and facilities available. The major exception is the extensive sensor research program at Tohoku University.

Tohoku University. The research program under Professor Masayoshi Esashi at Tohoku University appears to have by far the largest effort and best facilities directed at sensors R&D at Japanese universities. The facilities are modern and cover a broad range of capabilities, including microfabrication, electronic integration, and devices testing. These facilities are on a par with the best of the U.S. universities engaged in sensor research.

Efforts at Tohoku range from basic material and process development, to development of specific sensors, to specialized sensor packaging. Several sensors were reported as being successfully commercialized in the past, including two ion-sensitive field-effect transistors (ISFETs) for measuring pH and pCO_2, along with a capacitive pressure sensor. The integration of sensors and electronic circuitry is seen as a dominant trend, and much effort is being devoted to integrated packaging of sensors using glass-silicon bonding (Esashi 1993).

The current research projects on sensors include considerable work on a silicon capacitive accelerometer, including the use of electrostatic force rebalance for expanded dynamic range (Matsumoto and Esashi 1992). The device, shown in Figure 3.9, uses integrated capacitive readout circuitry, and an external phase-locked loop force rebalance circuit. The silicon proof mass is suspended from silicon oxynitride flexures, and the chip is sandwiched between glass covers that include the capacitor electrodes and holes for electrical leadouts, as well as providing overrange protection and damping. The accelerometer operates over the range of a few gravities with good linearity.

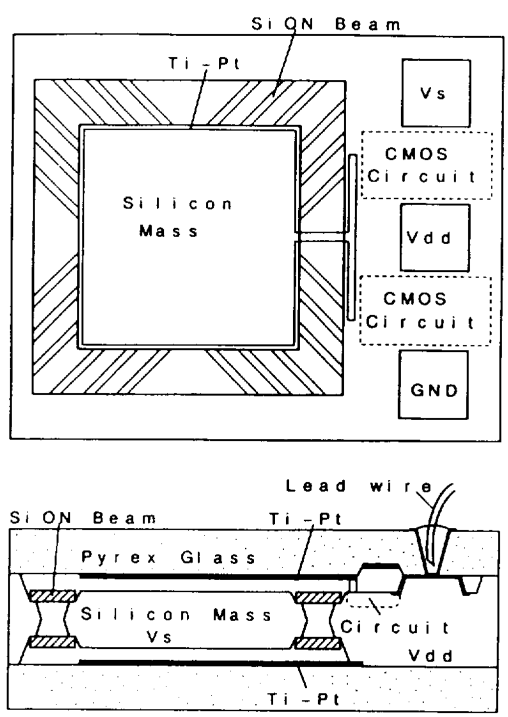


Figure 3.9. Tohoku University integrated capacitive accelerometer (Matsumoto and Esashi 1992).

Also developed at Tohoku is the integrated capacitive silicon pressure sensor shown in Figure 3.10 (Matsumoto, Shoji, and Esashi 1990). A Pyrex glass cover is sealed to provide a vacuum reference cavity. The silicon chip includes a bossed sensor diaphragm and CMOS capacitance-to-frequency converter circuitry. The full span was 600 mmHg, with a frequency scale factor of 30 Hz/mmHg. This device technology was probably the pressure sensor described as being commercialized.

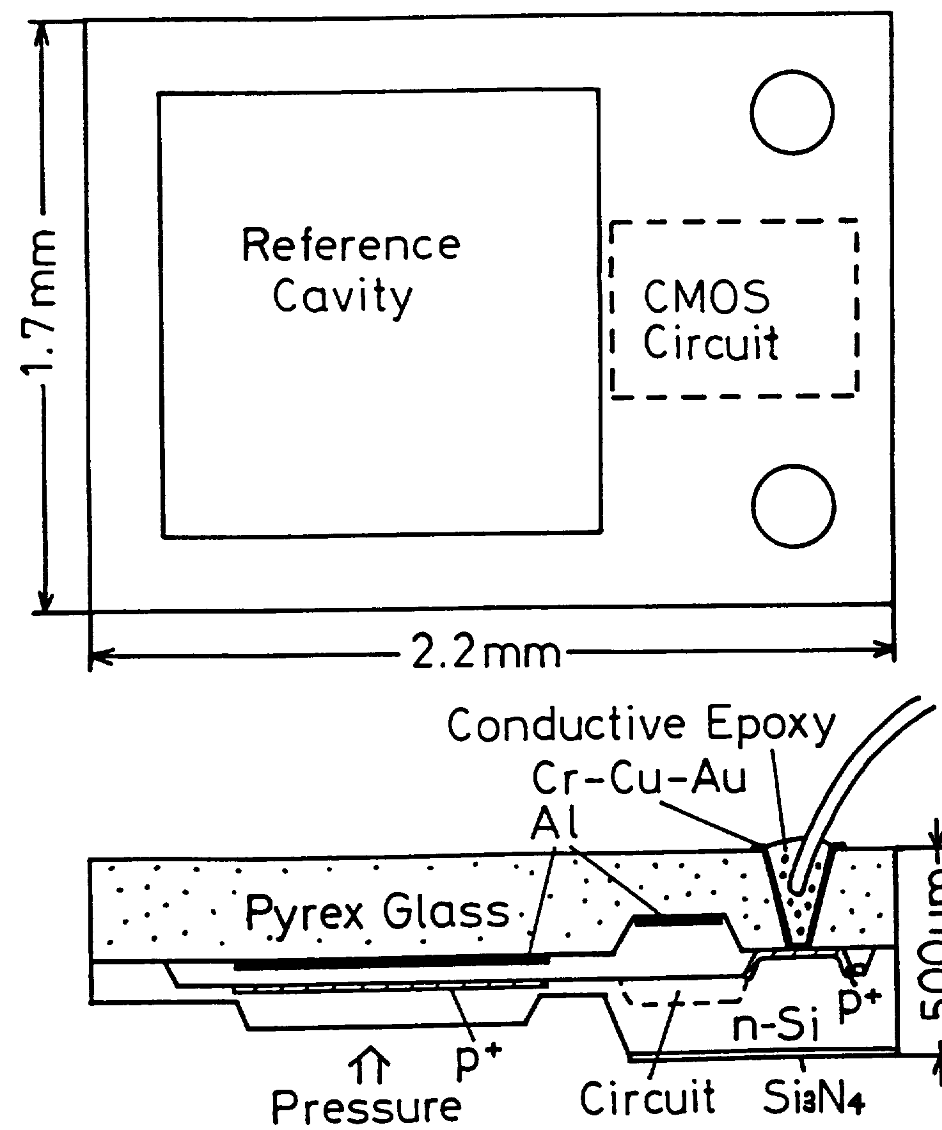


Figure 3.10. Tohoku University integrated capacitive pressure sensor (Matsumoto, Shoji, and Esashi 1990).

Another device is a resonant infrared radiation (IR) sensor, which combines bulk silicon micromachining, on-chip NMOS circuitry, and vacuum packaging by silicon-to-glass bonding (Cabuz et al. 1993). The principles of operation involve measuring the change in frequency of a silicon microstructure resonator induced by mechanical stresses due to the heating by incident IR. Frequency sensitivities of about 300 ppm/μW were observed. Also reported were a thermal mass flowmeter and integrated paramagnetic oxygen sensor based on the flow sensor (Esashi 1991). This device combines silicon micromachining and silicon-glass bonding for its fabrication.

Others. The research efforts of Professor M. Kimura at Tohoku-Gakuin University include MEMS-based sensor developments. The Tohoku-Gakuin laboratory facilities are well laid out, using mostly donated equipment, but somewhat limited in capabilities. Professor Kimura works with industry to license his patents and transfer his technology.

One thrust of Professor Kimura's research has been on devices based on thermal isolation bridge microstructures. These have been used for flow and infrared sensors, for example (Kimura 1986). Some gas sensor development by the Ricoh Company is based on this work.

No significant MEMS-based sensor development was discussed at the other Japanese universities JTEC visited. The recent sensor publications from Japanese universities are also limited in number and scope.

Gas, Chemical, and Humidity Sensing

There is excellent work going on at Japanese universities and industry in the areas of microminiature solid state gas, chemical, and humidity sensors, where Japan appears to be doing considerably more research than the United States. For example, the review paper by Yamazoe and Miura at Transducers '93 gives an excellent summary of solid state gas sensor research (1993). These devices do not come under the present definition of MEMS or within the expertise of the panel, and are not included in the present study. However, solid state gas sensor research is an area of strong Japanese capability.

Role of the National Micromachine Technology Project

Sensors listed as required for MITI's micromachine program (Micromachine Center 1993) include microgyroscopes, ultrasonic sensors, and miniature vision and optical sensors. At this stage, the national micromachine program appears to have little effect on the development of sensor technology. MEMS sensor technology is already well advanced, largely based on silicon microfabrication, and enjoying considerable commercial application. The MITI micromachine effort is much more focused on micromachines, microactuators, and so forth. The sensors required seem not yet clearly defined, but may use nonsilicon approaches in many cases. Sensors do not appear to be critical, pacing items in either the national micromachine project or in other micromachine or microrobotic developments.

COMPARISON WITH SENSOR DEVELOPMENT IN THE UNITED STATES

This section will describe major MEMS-based sensor developments in the United States and compare them with similar activities in Japan. This section also will show that, based on published information, there is greater diversity of MEMS sensor types and applications in the United States, due in part to the strength of U.S. university research. It may also be due to different approaches to publication and publicity, and the panel's imperfect knowledge of Japanese work. Also, Japanese industry focuses on a smaller number of sensors and applications that are deemed of greatest commercial importance. Finally, as noted from the discussion in a previous section, there are other areas of solid-state sensors such as gas, chemical, and humidity sensing, where Japanese efforts are greater than those of the United States.

There are major MEMS sensor efforts in both the United States and Japan on the development of advanced silicon pressure sensors and silicon accelerometers. These efforts are primarily driven by existing and potential high-volume applications in automotive, medical, commercial, and consumer products. The most important requirements are typically for moderate performance at very low cost. The batch fabricated nature of MEMS sensors addresses these needs, along with advantages of small size and low power. Development efforts also address high-performance needs in military and industrial systems. Many pressure sensors and accelerometers with significant levels of electronic integration are under development or even in production in both countries, while others may be expected in the marketplace in the next three to five years.

While bulk micromachined silicon diaphragm pressure sensors have been commonplace for many years, recent developments are resulting in significantly smaller and potentially less expensive devices. These devices are most suitable for low to moderate performance applications where cost and perhaps size are critical, such as disposable medical sensors and consumer products. One technique developed in the United States at the University of Wisconsin uses thin film polysilicon for the sensor diaphragm (Guckel et al. 1987). Because the polysilicon diaphragm is only about one-tenth the thickness of conventional silicon pressure sensor diaphragms, the polysilicon devices are correspondingly smaller. Thus there are many times more sensor dies per wafer, and the cost is much lower. Developments at Toyota using thin film nitride diaphragms were described above (Shimaoka et al. 1993).

Another technique, originated by NovaSensor in the United States, employs high temperature fusion bonding of silicon wafers to form inward tapering cavities under single crystal silicon diaphragms (Petersen et al. 1988). This technique can also result in much smaller sensor dies than standard bulk micromachining techniques. These devices are used in medical catheters, where size and cost are critical. No comparable work has appeared in Japan, although many industrial laboratories have wafer bonding technology.

Many pressure sensing applications may require measurement of low pressures in the range of 1,000 Pa, but adequate sensitivity to such low pressure is not easily accomplished with conventional bulk micromachined sensors. However, by using advanced MEMS micromachining technology to add corrugations or bosses to the diaphragm, areas of stress concentration can be formed that facilitate these low pressure measurements (Mallon et al. 1990). Several such low pressure micromachined sensors are commercially available in the United States.

Technology for miniature resonant strain sensors has been demonstrated both in the United States (Guckel et al. 1992; Petersen et al. 1991) and Japan (Ikeda et al. 1988, 1990a, 1990b), that may replace capacitive or piezoresistive readout of silicon diaphragm pressure sensors for improved performance. The devices employ a miniature beam driven into mechanical resonance by feedback electronics. The resonant frequency is a sensitive measure of strain, but is relatively insensitive to temperature or to the electrical properties of the device. The devices are located on a conventional silicon pressure sensor diaphragm where they function as frequency output strain gauges. There are no critical analog gain stages, and the frequency output is easily interfaced to digital signal processing circuitry. In the Guckel and Ikeda approaches, a vacuum shell can be integrally formed around the beam to allow operation in any media. The mechanical complexity and very small size required is made possible only by advances in MEMS technology. Japan is ahead in this technology and its commercialization, as described above in the work by Yokogawa.

Because of the large potential markets in automotive applications for sensors for air bag deployment and active suspensions, there are many efforts under way in the United States and Japan to develop miniature silicon accelerometers. MEMS technology is key to achieving the required performance combined with the low sensor costs demanded by these applications. Several accelerometers using bulk silicon micromachining to form a single crystal silicon proof mass and supporting flexures have been developed in the United States (Barth et al. 1988; Terry 1988) and Japan (Koide et al. 1992; Muro et al. 1992), and some are commercially available. Either piezoresistive or capacitive readout of proof mass displacement can be employed. These devices also use multiple wafer bonding technology to fabricate sandwich structures to provide overrange protection and damping. More recently, microminiature accelerometers fabricated in polysilicon by surface micromachining were reported by U.S. companies such as Analog Devices (Payne and Dinsmore 1991) and Motorola (Ristic 1992). No similar Japanese devices have been reported, but again, the technology capabilities are in place. These accelerometers may also be integrated with CMOS electronics. Several commercial products are available.

Higher performance accelerometer applications such as inertial navigation are being addressed at several laboratories. Closed loop silicon accelerometers have been reported in the United States and Japan. Several use bulk silicon structures (Henrion et al. 1990; Tsuchitani et al. 1991; Matsumoto and Esashi 1992), another employs a surface micromachined single-crystal structure (Boxenhorn and Greiff 1990), and still another consists of a polysilicon accelerometer integrated with CMOS detection circuitry (Yun, Howe, and Gray 1992). Open-loop accelerometers using resonant strain sensors are under development at Sundstrand.

For critical applications such as air bag deployment, efforts are under way in the United States to develop self-test capability in accelerometers. In one such device (Allen, Terry, and DeBruin 1990), an input signal heats an actuation beam that applies a known force to the device structure. Another concept uses electrostatic forces to apply the test signal to the accelerometer (Pourahmadi, Christel, and Petersen 1992). If proper response is obtained, the functionality of the accelerometer is confirmed. Self-test concepts have not been reported by Japanese researchers, but could easily be developed.

Several other types of sensors for mechanical variables are being developed in the United States, driven by military applications. No equivalent developments appear in Japanese publications. Vibratory silicon gyroscopes have been demonstrated by Draper Lab (Greiff et al. 1991) and by Sundstrand (Hulsing and MacGugan 1993). The Draper gyro is a doubly gimbaled structure supported by torsional flexures. The gimbaled mass is driven into torsional vibration, and Coriolis forces during rotation transfer energy into vibration in the orthogonal torsional mode. The amplitude of this second vibration is a measure of input rotation rate. The Sundstrand gyro concept uses Coriolis effects on a dithered pair of precision accelerometers, and is projected capable of measuring rates approaching 1°/hr. A micromachined silicon condenser hydrophone has been reported (Bernstein 1992). This device uses a surface micromachined silicon plate that is deflected by the acoustic wave, causing a capacitance change with respect to an overlying micromachined electrode. High acoustic sensitivity is obtained in a device only 1 mm on a side, comparable to ferroelectric hydrophones many times larger.

Complex, micromachined structures can be designed and fabricated to have unique thermal properties that can be useful for sensors: (1) Microminiature versions of thermal mass flowmeters have been demonstrated to be more sensitive and faster responding, and require lower power than macroscopic devices (Ohnstein et al. 1990; Tai, Muller, and Howe 1985). While the basic thermal principles of operation are similar, the miniature devices have significantly better performance due solely to their small size. (2) A fully integrated, miniature Pirani vacuum gauge (Mastrangelo and Muller 1991) measures absolute pressure between 10^1 to 10^4 Pa by the pressure dependent change in thermal conductivity. The MEMS device is very low in power, and is fully integrated with NMOS circuitry giving a digital output. (3) Microstructure bolometer devices have useful sensitivity to infrared radiation and can be easily fabricated as arrays of miniature devices. Thermal infrared detectors and small arrays have been developed in the United States (Choi and Wise 1986) and in Japan (Tanaka et al. 1992; Asahi et al. 1993). Work in the United States is far ahead, where very large imaging arrays of 200,000 pixels with high sensitivity and low noise-equivalent temperature difference, and complete integrated readout electronics have been produced (Wood, Han, and Kruse 1992).

MEMS technology is also being advantageously combined with optics for sensing in the United States. One example is the fabrication of a miniature Fabry-Perot interferometer for optical measurements in the near infrared spectral region (Jerman 1990). Another demonstration is use of light beams to excite a microminiature resonant beam strain sensor and sense the beam's vibrational motion (Guckel et al. 1993).

In an advanced concept, micromachined structures have been fabricated as extremely sensitive displacement transducers using electron tunneling concepts. The devices employ a microfabricated tunneling tip in close proximity to a surface. Resolution of 10^{-2} Å displacements between tip and surface by variation in the tunnel current have been demonstrated (Kenney et al. 1991). Applications to Golay cell infrared detectors, accelerometers, and seismometers are being explored. Such extremely high displacement sensitivity raises questions of dynamic range and stability that must be addressed. Japanese researchers have not reported on sensing applications to the tunnel sensor, but they are using silicon microstructures for scanning-tunneling microscopes (STMs), and are easily capable of developing such sensors.

As described above, there are many significant developments under way both in the United States and Japan for improved sensors and sensors for new variables, with new structures and operating principles, with improved performance, and reduced cost. However, many issues remain for developments in both countries in addressing potential practical applications. The specialized nature of many MEMS fabrication processes makes cost-effective fabrication an issue for low to moderate volume applications. High reliability and stability in the real operating environment are critical requirements for many sensors. These requirements are difficult to achieve, and continued development is required for many applications and products.

The important questions of cost, reliability, and performance go beyond the basic sensor element itself. The sensor package can have a dominant effect. New packaging and assembly schemes, including integrated wafer-level packaging, are being developed to address these issues, and are described in another section of this report. Finally, integration of sensors and electronic circuitry into more sophisticated instrumentation subsystems is an increasing trend. The smart sensors can provide compensation, linearization, output ranging, two-way communication, and many other functions.

SUMMARY AND CONCLUSIONS

MEMS-based sensor technology capabilities in Japanese and U.S. industrial laboratories appear largely comparable in quality and state of the art, and in technology and applications focus. There are major efforts on both bulk and surface micromachined devices, on the use of wafer bonding for integrated sensor packaging, and on integration of electronic circuitry with sensors. Both emphasize high-volume applications, such as automotive, and important sensors, such as pressure and accelerometers. High performance devices such as precision pressure sensors are under development in both countries. MEMS-based development of a variety of more complex sensors driven by military applications is relatively strong in the United States, but there is no equivalent effort in Japan.

The United States generally appears to have a lead in demonstration of innovative new materials and process technologies for MEMS-based sensors, and in the first demonstration and commercialization of new device concepts. Much of this lead derives from innovative research at U.S. universities, and from entrepreneurial start-up companies.

MEMS sensor R&D at U.S. universities is a major area of strength compared to Japan. The top U.S. universities in sensor research -- including Berkeley, Michigan, MIT, Wisconsin, and others -- are superior to those in Japan, with the exception of Tohoku University. This superiority exists in the quality of the facilities, the breadth of capabilities in both microfabrication and testing, and the critical mass of students and faculty. There is a vast array of technology under development in U.S. universities, where students are receiving excellent training. If this technology is appropriately focused on high-payoff applications and transferred in a timely and cost-effective manner, it can provide major technological advantages for U.S. industry.

MEMS-based sensors are being commercialized in the U.S. by companies in the sensor component, electronic component, and systems businesses. U.S. industry appears to be producing more innovative sensor technologies and commercial sensor products somewhat earlier than Japan. The presence of many innovative, entrepreneurial sensor start-ups has driven the commercialization of solid-state sensor technology in the United States, and is a major difference between the United

States and Japan. Examples of these smaller, high-technology sensor companies include NovaSensor and IC Sensors. They have produced basic technology innovations such as silicon fusion bonding, have driven the costs down for high volume products such as medical pressure sensors, and have been responsible for the first commercial introductions of a variety of new MEMS-based sensors. Their presence creates a competitive and innovative environment, and probably also forces larger companies in the United States to commercialize more rapidly. No equivalent entrepreneurial start-ups exist in Japan, and this may be partly responsible for an apparently slower pace of innovation and commercialization there.

In summary, the U.S. MEMS sensor technology base is, in general, comparable to that of Japan and somewhat ahead in development of new processes and new device concepts. This technology base does not appear to be a limiting factor in U.S. competitiveness now or in the foreseeable future. U.S. advantages include superior university research, and competition and innovation in the marketplace. However, Japanese MEMS sensor technology capability is strong, and certainly not far behind that of the United States. Japanese development efforts are focused on the most important commercial applications. Japanese companies now have and will continue to have products to market in time to meet the most important application opportunities. Success in business based on MEMS sensor technology will be greatly dependent on the vision, strategic planning, and investment decisions of industry, and on the ability to appropriately and cost-effectively commercialize this technology into innovative products in a timely fashion.

REFERENCES

Allen, H., S. Terry, and D. DeBruin. 1990. "Accelerometer with Built-In Self Testing." *Sensors and Actuators*. A21-A23:381-386.

Asahi, R., J. Sakata, O. Tabata, M. Mochizuki, S. Sugiyama, and Y. Taga. 1993. "Integrated Pyroelectric Infrared Sensor Using PVDF Thin Film Deposited by Electro-Spray Method." Paper presented at Transducers '93. Yokohama.

Barth, P., F. Pourahmadi, R. Mayer, J. Polydock, and K. Petersen. 1988. "A Monolithic Silicon Accelerometer with Integral Air Damping and Overrange Protection." Paper presented at 1988 IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Bernstein, J. 1992. "A Micromachined Condenser Hydrophone." Paper presented at 1992 IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Boxenhorn, B., and P. Greiff. 1990. "Monolithic Silicon Accelerometer." *Sensors and Actuators*. A21-A23:273-277.

Cabuz, C., S. Shoji, K. Fukatsu, E. Cabuz, K. Minami, and M. Esashi. 1993. "Highly Sensitive Resonant Infrared Sensor." Paper presented at Transducers '93. Yokohama.

Choi, I., and K. Wise. 1986. "A Silicon-Thermopile-Based Infrared Sensing Array for Use in Automated Manufacturing." *IEEE Trans. on Electron Devices*. 33:72-79.

Esashi, M. 1991. "Micro Flow Sensor and Integrated Magnetic Oxygen Sensor Using It." Paper presented at Transducers '91. San Francisco.

Esashi, M. 1993. "Micromachining for Packaged Sensors." Paper presented at Transducers '93. Yokohama.

Fujii, T., Y. Gotoh, S. Yoshihara, and M. Ohkawa. 1990. "Dielectrically Isolated Silicon Diaphragm Formation Utilizing a Wafer Bonding Method and Stress Evaluation." In *Technical Digest of The 9th Sensor Symposium*.

Fujii, T., Y. Gotoh, and S. Kuroyanagi. 1992. "Fabrication of Microdiaphragm Pressure Sensor Utilizing Micromachining." *Sensors and Actuators*. A34:217-224.

Greiff, P., B. Boxenhorn, T. King, and L. Niles. 1991. "Silicon Monolithic Micromechanical Gyroscope." Paper presented at Transducers '91. San Francisco.

Guckel, H., D. Burns, C. Rutigliano, D. Showers, and J. Uglow. 1987. "Fine Grained Polysilicon and its Application to Planar Pressure Transducers." Paper presented at Transducers '87. Tokyo.

Guckel, H., C. Rypstat, M. Nesnidal, J. Zook, D. Burns, and D. Arch. 1992. "Polysilicon Resonant Microbeam Technology for High Performance Sensor Applications." Paper presented at IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Guckel, H., M. Nesnidal, J. Zook, and D. Burns. 1993. "Optical Drive/Sense for High Q Resonant Microbeams." Paper presented at Transducers '93. Yokohama.

Henrion, W., L. DiSanza, M. Ip, S. Terry, and H. Jerman. 1990. "Wide Dynamic Range Direct Digital Accelerometer." Paper presented at 1990 IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Hulsing, R., and D. MacGugan. 1993. "Miniature IMU Based on Micro-machined Coriolis Sensors." Paper presented at Institute of Navigation 1993 Technical Meeting. San Francisco.

Ikeda, K., et al. 1988. "Silicon Pressure Sensor with Resonant Strain Gauge Built into Diaphragm." In *Technical Digest of the 7th Sensor Symposium.*

Ikeda, K., H. Kuwayama, T. Kobayashi, T. Watanabe, T. Nishikawa, T. Yoshida, and K. Harada. 1990a. "Silicon Pressure Sensor Integrates Resonant Strain Gauge on Diaphragm." *Sensors and Actuators.* A21-A23:146-150.

Ikeda, K., H. Kuwayama, T. Kobayashi, T. Watanabe, T. Nishikawa, T. Yoshida, and K. Harada. 1990b. "Three-dimensional Micromachining of Silicon Pressure Sensor Integrating Resonant Strain Gauge on Diaphragm." *Sensors and Actuators.* A21-A23:1007-1009.

Itoh, T., T. Adachi, and H. Hashimoto. 1992. "One-Chip Integrated Pressure Sensor." In *Technical Digest of the 11th Sensor Symposium.*

Jerman, J. 1990. "A Miniature Fabry-Perot Interferometer with a Corrugated Silicon Diaphragm Support." Paper presented at 1990 IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Kato, K., Y. Muramatsu, H. Fujimoto, and O. Sasaki. 1991. "Totally Integrated Semiconductor Pressure Sensor." In *Technical Digest of the 10th Sensor Symposium.*

Kenney, T., S. Waltman, J. Reynolds, and W. Kaiser. 1991. "Micromachined Silicon Tunnel Sensor for Motion Detection." *Applied Physics Letters.* 58:100-102.

Kimura, M. 1986. "Infrared Sensor with Micro-Air-Bridges of a-Si(h) Film." In *Technical Digest of the 6th Sensor Symposium.*

Koide, A., K. Sato, S. Suzuki, and M. Miki. 1992. "A Multistep Anisotropic Etching Process for Producing 3-D Accelerometers." In *Technical Digest of the 11th Sensor Symposium.*

Mallon, J., F. Pourahmadi, K. Petersen, P. Barth, T. Vermeulen, and J. Bryzek. 1990. "Low-Pressure Sensors Employing Bossed Diaphragms and Precision Etch-Stopping." *Sensors and Actuators.* A21-23:89.

Mastrangelo, C., and R. Muller. 1991. "Fabrication and Performance of a Fully Integrated μ-Pirani Pressure Gauge with Digital Readout." Paper presented at Transducers '91. San Francisco.

Matsumoto, Y., and M. Esashi. 1992. "Integrated Capacitive Accelerometer with Novel Electrostatic Force Balancing." In *Technical Digest of the 11th Sensor Symposium.*

Matsumoto, Y., S. Shoji, and M. Esashi. 1990. "A Miniature Integrated Capacitive Pressure Sensor." In *Technical Digest of the 9th Sensor Symposium.*

Micromachine Center. 1993. Chart presented to JTEC MEMS panel.

Morikawa, T., Y. Nonomura, K. Tsukuda, M. Takeuchi, A. Honsono, and M. Kawai. 1993. "3-Dimensional Piezoresistive FEM Analysis of a New Combustion Pressure Sensor." Paper presented at Transducers '93. Yokohama.

Muro, H., H. Kaneko, S. Kiyota, and P.J. French. 1992. "Stress Analysis of SiO_2/Si Bimetal Effect in Silicon Accelerometers and its Compensation." *Sensors and Actuators.* A34:43-49.

Nagata, T., H. Terabe, S. Kuwahara, S. Sakurai, O. Tabata, S. Sugiyama, and M. Esashi. 1992a. "Digital Compensated Capacitive Pressure Sensor Using CMOS Technology for Low-pressure Measurements." *Sensors and Actuators.* A34:173-177.

Nagata, T., Y. Fukaya, Y. Hattori, T. Sato, S. Sakurai, and M. Esashi. 1992b. "A CMOS Integrated Capacitive Accelerometer with a Self-Test Function." In *Technical Digest of the 11th Sensor Symposium.*

Ohnstein, T., R. Johnson, R. Higashi, D. Burns, J. Holmen, E. Satren, G. Johnson, R. Bicking, and S. Johnson. 1990. "Environmentally Rugged, Wide Dynamic Range Microstructure Airflow Sensor." Paper presented at 1990 IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Payne, R.S., and K.A. Dinsmore. 1991. "Surface Micromachined Accelerometer: A Technology Update." Paper presented at SAE, Detroit.

Petersen, K., P. Barth, J. Polydock, J. Brown, J. Mallon, and J. Bryzek. 1988. "Silicon Fusion Bonding for Pressure Sensors." Paper presented at 1988 IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Petersen, K., F. Pourahmadi, J. Brown, P. Parsons, M. Skinner, and J. Tudor. 1991. "Resonant Beam Pressure Sensor Fabricated with Silicon Fusion Bonding." Paper presented at Transducers '91. San Francisco.

Pourahmadi, F., L. Christel, and K. Petersen. 1992. "Silicon Accelerometer with New Thermal Self-Test Mechanism." Paper presented at 1992 IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Ristic, L. 1992. "Surface Micromachined Polysilicon Accelerometer." Paper presented at 1992 IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Saito, K., T. Nishikawa, H. Kuwayama, K. Yoshioka, and S. Zager. 1992. "A Resonant Monolithic Silicon Sensor for Intelligent DP Transmitters." Paper presented at Instrument Society of America.

Shimaoka, K., O. Tabata, M. Kimura, and S. Sugiyama. 1993. "Micro-Diaphragm Pressure Sensor Using Polysilicon Sacrificial Layer Etch-Stop Technique." Paper presented at Transducers '93. Yokohama.

Sugiyama, S., K. Kawahata, M. Yoneda, and I. Igarashi. 1990. "Tactile Image Detection Using a 1K-element Silicon Pressure Sensor Array." *Sensors and Actuators.* A21-A23:397-400.

Tai, T., R. Muller, and R. Howe. 1985. "Polysilicon Bridges for Anemometer Applications." Paper presented at Transducers '85. Philadelphia.

Tanaka, A., M. Suzuki, R. Asahi, O. Tabata, and S. Sugiyama. 1992. "Infrared Linear Image Sensor Using A Poly-Si pn Junction Diode Array." *Infrared Physics.* 33:229-236.

Terry, S. 1988. "A Miniature Silicon Accelerometer with Built-In Damping." Paper presented at IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Tsuchitani, S., et al. 1991. "Study of the Behavior of a PWM Electrostatic Servo Accelerometer." In *Technical Digest of the 10th Sensor Symposium.*

Wood, R.A., C. Han, and P. Kruse. 1992. "Integrated Uncooled Infrared Detector Imaging Array." Paper presented at IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

Yamashita, S., K. Shimaoka, H. Funabashi, S. Sugiyama, and I. Igarashi. 1989. "A Fully Integrated Pressure Sensor." In *Technical Digest of the 8th Sensor Symposium.*

Yamazoe, N., and N. Miura. 1993. "Environmental Gas Sensing." Paper presented at Transducers '93. Tokyo.

Yun, W., R. Howe, and P. Gray. 1992."Surface Micromachined, Digitally Force-Balanced Accelerometer with Integrated CMOS Detection Circuitry." Paper presented at 1992 IEEE Solid-State Sensor and Actuator Workshop. Hilton Head Island.

CHAPTER 4

MICROACTUATORS

Richard S. Muller

INTRODUCTION

Although MEMS without microactuators is possible, and such important commercial implementations as those for pressure sensing and large-array IR vidicons are built with entirely static micromechanical structures, microactuation opens a universe of important new opportunities to microsystems. These opportunities may be hidden within the systems, as in the extremely important case of providing microactuated mechanical-feedback links, or they may make possible the system function itself, as in an ink-jet or a micropositioner. In the first case, it becomes vital to think in terms of practical compatible electronic or optical-device fabrication procedures; whereas, in the second case, compatible fabrication of the actuator together with the microelectronic circuit is merely preferable, but not critical.

The dual thrust of the MEMS program in Japan -- toward lithography and silicon-based systems on the one hand, and toward ultraminiaturization using downsizing of conventional mechanical design, on the other -- exerts a strong influence on what can reasonably be conceived of as practical approaches for actuation.

DEVELOPMENTS IN JAPAN

These and other generalized concepts about microactuators formed a basis for comparing microactuation efforts in Japan and the United States. Table 4.1 summarizes some impressions gained by the JTEC panel during its review of actuation activities within the MEMS area.

Table 4.1
Microactuation Activity in Japan

SUMMARY
Range of Techniques Under Consideration
Very Small (mm-sized) EM Motors Built
Major Activity in Piezoactuators
Increasing Focus on Ultrasonic Motors
SMA in Use (Especially for Endoscopes and Catheters)
Electrostatic Drive Being Used in Diverse Areas
Unusual Techniques Being Investigated

An illustration of the broad range of microactuation techniques under study in Japan is provided by the MITI Micromachine Technology Project. Table 4.2 is a map of the elemental technologies for MITI's Mother Ship and Microcapsule project, which has provided a focus for twenty-four laboratories in Japan and three foreign laboratories. As seen in Table 4.2, the map shows a total of eleven actuation mechanisms being considered for the MITI project alone. Only a few of these mechanisms are associated directly with lithography-based manufacture, especially with manufacture that employs IC-derived processes and materials.

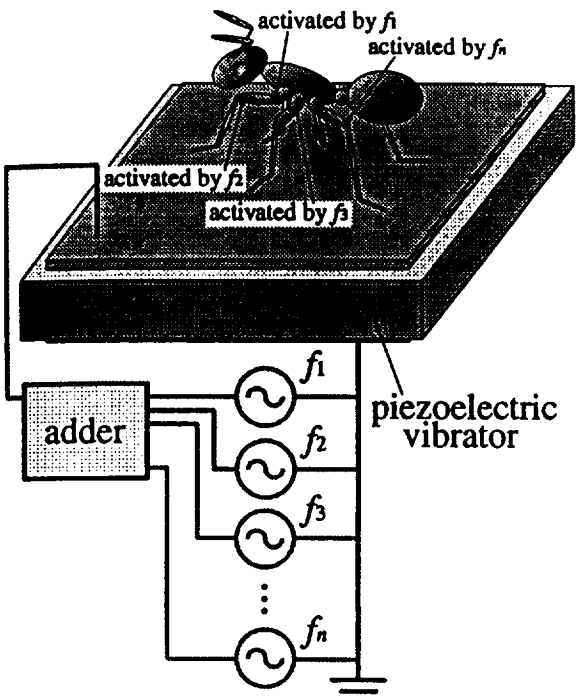
One of the laboratories in Japan that specializes in microactuation using lithography-based processing operates within the Institute of Industrial Science (IIS) at the University of Tokyo (Roppongi Campus). There a Research Group of Excellence in Micromechatronics has been formed under the leadership of Professor Hiroyuki Fujita. This group joins the research of seven professors "to integrate micromachines and microelectronics into a complete mechatronics system which works in the microworld." At IIS there are substantial ties with industrial laboratories such as IBM Research in Tokyo, with which the Fujita group has joined to study the production of needle bearings that are able to support micromotor rotors (of near hair's breadth dimensions) that turn at more than 10,000 rpm under electrostatic drive (Hirano, Furuhata, and Fujita 1993). Other impressive Fujita-lab actuator work has been the development of thermobimorph actuators fabricated in large arrays so that the 500-micron bimorphs are able to move small objects placed upon them by ciliary motion (much as objects are moved within the animal throat by cilia) (Ataka, Omodaka, and Fujita 1993). Fujita's group is looking very broadly at IC-based technologies to develop a wide scope of actuation means. An example that demonstrates the scope is an actuator system in which an electrostatically operated polyimide valve is used to direct a microstream of air in order to push an object in a specified direction on a surface (Konishi and Fujita 1993).

Table 4.2
Elemental Technology Map

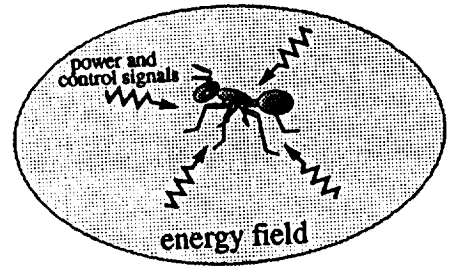
	Micro Capsule	Mother Ship	Inspection Module (without wire)	Operation Module (with wire)
Energy Supply	Micro dynamo	Micro battery (Hydrogen absorption alloy)	Microwave transmission Photo-electric conversion (solar battery type)	Photo-electric conversion (p-n junction type)
Actuator Mechanism	Electromagnetic motor for steering Speed increaser	Pneumatic clamping Electrostatic driving mechanism	Inching worm driving mechanism Piezoelectric motion drive Functional connection	SMA manipulator Photo stimulated operation Gear train Locomotion High power source
Sensor	Ultrasonic detection Micro gyroscope	Photo-scanning device	Ultrasonic micro sonar Micro visual sensor Micro photo spectroscopy	Environment recognition by image fiber
Communi-cation	Signal transmission by piezo composite		Communication network	
Control	Dynamic motion control	Behavior control Group control	Teleoperation Coordination control	Multi-joint manipulator control

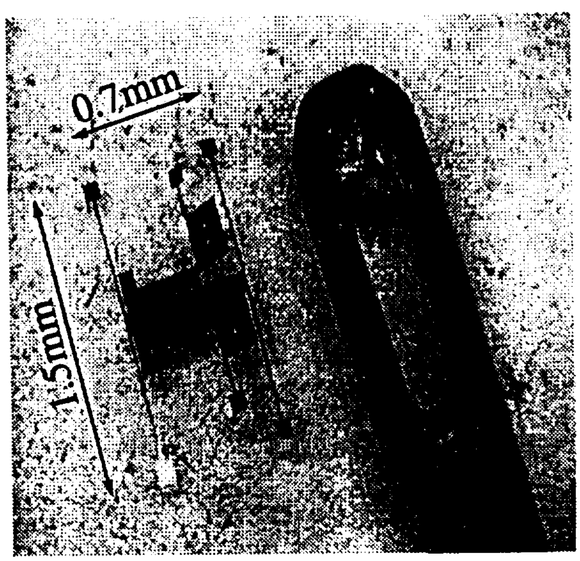
Also at the University of Tokyo, but not within the Institute of Industrial Science, Professor Hirofumi Miura is leading a group with actuation interests. The presentation by this group of a mechanical ant, which is energized by selective resonant coupling to tuned limbs that provide a walking motion, was very well received at the 1993 International Conference on Sensors and Actuators, held in June in Yokohama (Yasuda, Shimoyama, and Miura 1993). This novel concept is shown in Figure 4.1.

At the University of Nagoya, an active group is focusing on microactuation with a particular interest in the construction of microrobotic systems. Professor Toshio Fukuda and colleagues have shown tiny (millimeter-sized) objects in which electromagnetic resonators carried onboard and powered with small wires cause motion by the action of bent legs that move selectively in one preferred direction (1992). This investigation is a step forward in a project that Fukuda and his associates believe will produce self-organizing robotic systems. Presently, the results are confined to elements and systems that are measured in millimeter dimensions, although the long-term goal is for such robotic systems to be shrunk sufficiently for activity within the body, eventually inside a living heart.



Concept of selective power supply.





Photograph of the microrobot alongside a sewing needle.

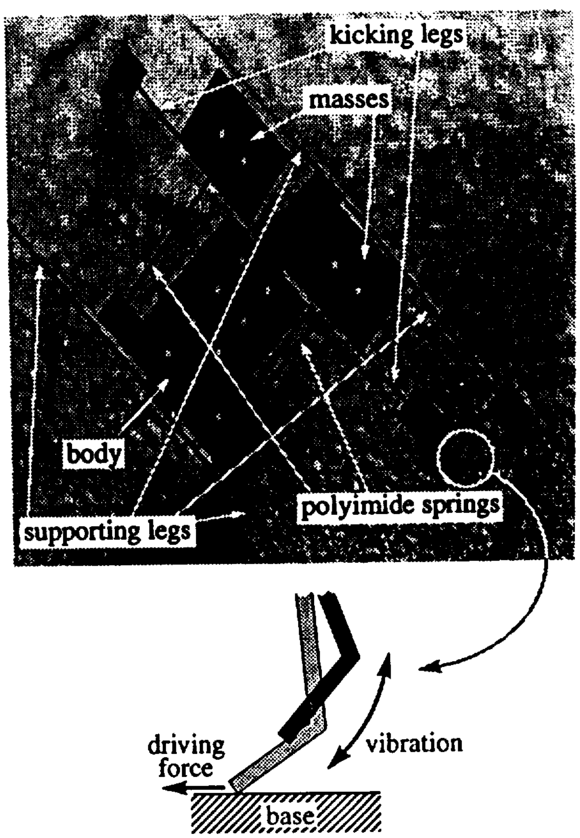


Figure 4.1. Mechanical ant actuated from a vibrating platform.

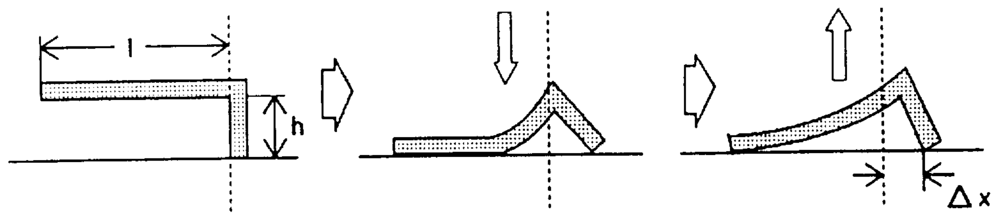
In the micron-scaled world which is much more adaptably approached via lithographic fabrication technologies, electrostatic actuation has been a very major focus. For surface-micromachined structures, polycrystalline silicon is the major building material at present both in Japan and the United States. Actuation using a stepping motion similar to that of the University of Nagoya's electromagnetic resonator microrobotic devices can also be accomplished via electrostatic drive, as is shown in the moving slider in Figure 4.2, which is described by T. Akiyama and K. Shono from Sophia University (Akiyama and Shono 1993).

A resonant electrostatic-drive mechanism is also employed to power an optical chopper of micron dimensions that was made at Toyota Central Research Laboratories by O. Tabata and associates (1993). The resonant-drive structure in this latter case is made by SOI (silicon-over-insulator) technology and is covered with aluminum as an absorber for the infrared signal that is to be chopped.

Another optical use for electrostatic actuation was demonstrated in the automatic focusing of a diaphragm mirror in a system built by K. Saeki and colleagues at the research laboratories of Nippondenso. This mirror-focus system capitalizes on IC-derived technology to produce economically a variable-thickness mirror so that optical aberration can be held to tolerable limits in a very small bar-code reading system (Saeki et al. 1992). A demonstration of this system at the Nippondenso Research Laboratory showed impressive performance.

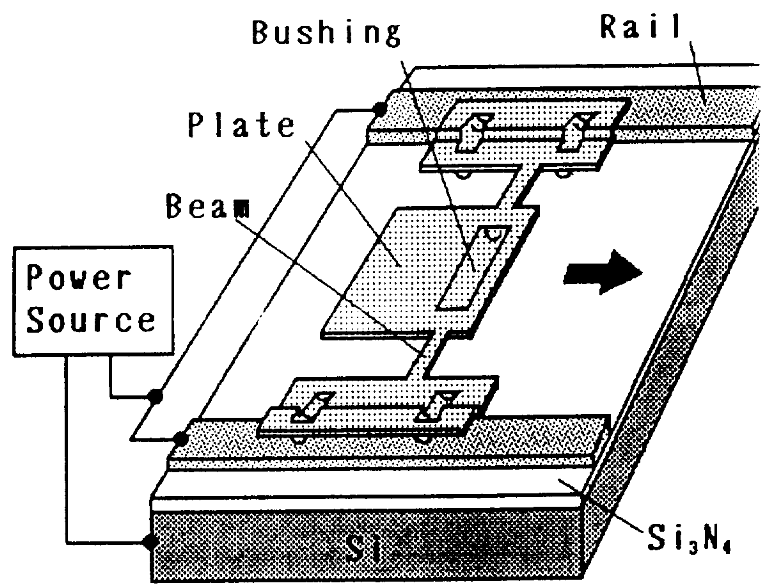
At the Hitachi Central Research Laboratory, M. Shikada and associates have used electrostatic drive on a conductive-diaphragm shutter to open and close a microfabricated gas valve (1993). The valve is appropriate for applications to gas-delivery systems for microelectronics fabrication equipment. Microflow systems are a topic of research and development at numerous Japanese research laboratories and industrial companies.

Extremely small-sized, conventionally designed electromagnetic motors are being produced by several large Japanese corporations, such as Nippondenso, Yasakawa, Seiko, Toshiba, Matsushita, and others. For example, Y. Tsutsui and his co-workers at Yasakawa used 0.2 mm diameter winding wires and thin-film magnets to produce a two-phase motor with a rotor 2.5 mm in diameter (1992). At Nippondenso, a microcar with a shell body that compares to rice-grain dimensions was powered by a microstepmotor having a 1.0 mm permanent-magnet rotor and achieving a micronewtonmeter of torque from a 3 V drive at 20 mA (Teshigahara 1992). In the lithography-based micromechanical arena, electromagnetic motors have not been demonstrated in Japan; however, work on magnetic levitation of rotating micromotors is being done by the H. Bleuler group at the Institute of Industrial Research at the University of Tokyo (Bleuler 1992).

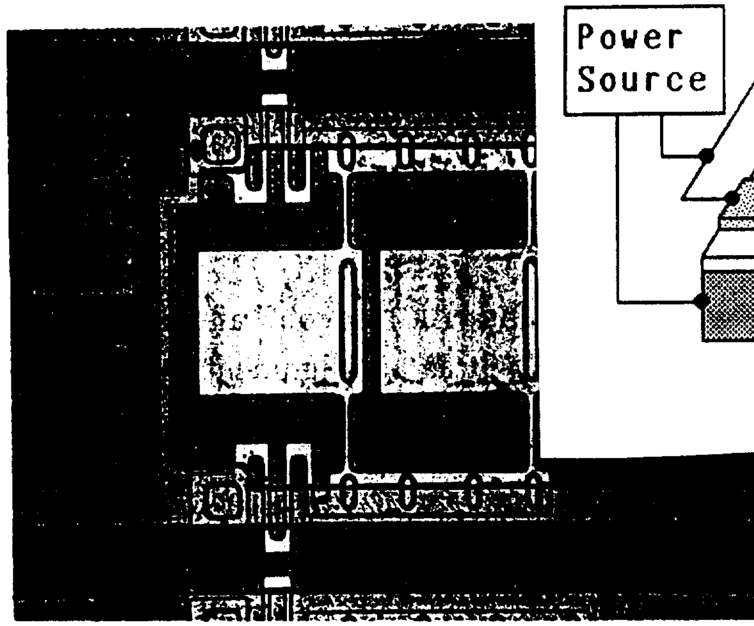


(a) (b) (c)

Cross sectional view of the polysilicon plate and bushing.



(a) schematic diagram



(b) microphotograph.

Figure 4.2. Electrostatically driven stepping microstructure.

A special area of microactuation needs is presented by the interest in Japan in steerable catheters and endoscopes. One project in the MITI micromachine initiative, the Intraluminal Diagnostic & Therapeutic System, is intended to develop catheters with both observation capabilities and tools on their ends to carry out remote-controlled diagnostics and therapies in blood vessels, in the alimentary canal, and in the pancreatic and bile ducts. The lead industrial laboratory for this research (which is being conducted by four companies) is that of Olympus Corporation, where similar research on the Olympus product line has comparable aims. The longer-range goal of the MITI program in this area is to produce catheter devices equipped with rotating ultrasound emitters and detection systems, vidicon camera units, fluid delivery and extraction systems, and manipulatable tools. At the present time, segmented shaped-memory alloy links made of TiNi alloys are being used to actuate catheter elements. Although details on performance are unavailable, problems with localized heating, speed of response, and reproducibility of the SMA actuators appear to be a research focus. Other approaches to actuation of the steerable catheter are still being considered and studied.

A major actuator trend in Japan is based upon piezoactuation. Several companies (including Canon, Seiko, NEC, Toto, Matsushita, Brother, Toyota, Mitsubishi, Hitachi, Nippondenso, Minolta, Fuji Electric, and others) are investigating both rotary and linear actuation using piezoactuators. Some of the application areas for piezoactuators are highlighted in a chart that was prepared by Professor K. Uchino at Pennsylvania State University. The chart, reproduced in Figure 4.3, shows the division of application areas of 550 piezoactuator patents issued in Japan between 1988 and 1990.

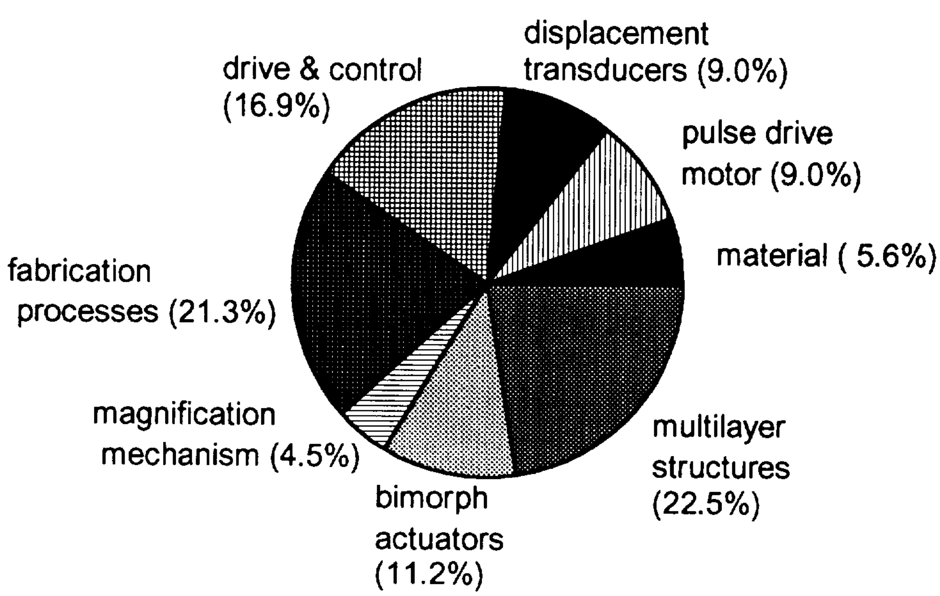


Figure 4.3. Distribution of patent topics for piezoactuators in Japan (1988 to 1990).

Exploitation of piezoactuators has been possible as a consequence of the controlled preparation of several highly active materials in sheet and thin-film form, most especially derivatives of PZT (lead zirconate titanate) and polyvinylidene fluoride. Properties of these materials are presented in Table 4.3, which was prepared by I. Seo of Mitsubishi Petrochemical Co.

Piezoactive materials are used extensively to drive ultrasonic motors. Early uses for the adjustment of camera lenses are well known. Recent improvements in materials have allowed them to be employed in window-closing and even seat-adjusting applications in the automotive field. The successful deposition of thin films allows piezoactuation to become an important candidate for microactuation in lithography-based fabrication. Recent results in this area at Toyota with PVDF are interesting and impressive.

SUMMARY AND CONCLUSIONS

This brief survey of microactuator work in Japan can be summarized as follows.

1. The development of microactuators is still in a relatively early phase -- a stage that makes it appropriate to support study of a wide range of approaches. This is an observation shared in the United States and Japan, but there is even wider diversity in the types of actuators under consideration in Japan than in the United States.

2. A particularly interesting prime mover that has applications both to mini- and microactuators is based upon piezoelectric materials used both for positioning and for ultrasonic motors. Success in this field is based on control of material properties. Present practice in Japan is well ahead of that in the United States.

3. Electrostatic actuation is widely used for diverse purposes. It is recognized as especially convenient when IC-compatibility is demanded. U.S. research on electrostatic actuation appears to be leading that of Japan.

4. Japanese expertise in the design of small electromagnetically-driven motors has enabled shrinkage of these elements to millimeter dimensions. This size appears to be near the limits of practicality for miniaturization by the downsizing of conventional machining. In the less than 100 micron realm, electromagnetic (EM) drive is under study in both the United States and Japan, and there appears to be a slight edge in the work practiced in the United States.

   Electromagnetic levitation for friction reduction is an important application of EM at the microlevel.

Table 4.3
Characteristics of Various Piezoelectric Materials
(Piezoelectric Characteristics in the Elongation Direction)

Physical Properties / Material	Density $10^3 kg/m^3$	Modulus of Elasticity $10^3 N/m^2$	Dielectric Constant	Piezoelectric Constants				Electro-Mechanical Combination Constant	Maximum Temperature Used °C
				$10^{-12} C/N$	$10^{-2} C/m^2$	$10^{-3} V\ m/N$	$10\ V/m$		
PVDF	1.78	3.0	13	29	6.0	174	53	0.10	80
P(VDF/TrFE) (VDF=55.%)	1.90	1.2	18	25	3.0	160	19	0.07	70
P(VDF/TrFE) (VDF=76%)	1.88	2.0	10	10	2.0	110	22	0.05	100
P(VDCN/VAc)	1.20	4.5	4.5	6	2.7	169	76	0.06	160
PVDF/PZT	5.3	3.0	120	29	6.0	19	6	0.07	100
Rubber/PZT	5.6	0.04	55	35	1.4	72	11	0.01	100
POM/PZT	4.5	2.0	95	17	3.4	20	4	0.08	140
Quartz	2.65	77.2	4.5	2	15.4	50	387	0.09	573
PZT	7.5	83.3	1200	110	920	10	87	0.31	250

Source: I. Seo, Mitsubishi Petrochemical Co.

5. The special demands of catheter and endoscope manipulation are driving efforts to make practical shape-memory-alloy actuators in Japan. SMA techniques appear to be more advanced in Japan than in the United States.

REFERENCES

Akiyama, T., and K. Shono. 1993. "A New Step Motion of Polysilicon Microstructures." In *Proceedings, IEEE Micro Electro Mechanical Systems Workshop*. Pp. 272-277.

Ataka, M., A. Omodaka, and H. Fujita. 1993. "A Biomimetic Micro Motion System, A Ciliary Motion System." In *Technical Digest, Transducers '93*. Pp. 38-41.

Bleuler, H. 1992. "Proposals for Active Micro Levitation." In *Technical Digest Volume, Third International Symposium on Micro Machine and Human Science*. Pp. 129-136.

Fukuda, T., N. Mitsumoto, F. Arai, and H. Matsuura. 1992. "Design and Experiment of Micro Mobile Robot Using Electro-magnetic Actuator." In *Tech. Digest Vol., Third International Symposium on Micro Machine and Human Science*. Pp. 77-82.

Hirano, T., T. Furuhata, and H. Fujita. 1993. "Dry Released Nickel Micromotors and Their Friction Characteristics." In *Tech. Digest, Transducers '93*. Pp. 80-83.

Konishi, S., and H. Fujita. 1993. "A Conveyance System Using Air Flow Based on the Concept of Distributed Micro Motion Systems." In *Tech. Digest, Transducers '93*. Pp. 28-31.

Saeki, K., T. Koumura, T. Kaneko, and T. Hattori. 1992. "Aberration Reduction of Si Diaphragm Dynamic Focusing Mirror." In *Tech. Digest Vol., Third International Symposium on Micro Machine and Human Science*. Pp. 83-88.

Shikada, M., K. Sato, S. Tanaka, Y. Kawamura, and Y. Fujisaki. 1993. "Electrostatically-Actuated Gas Valve with Large Conductance." In *Tech. Digest, Transducers '93*. Pp. 94-97.

Tabata, O., R. Asahi, N. Fujitsuka, M. Kimura, and S. Sugiyama. 1993. "Electrostatic Driven Optical Chopper Using SOI Wafer." In *Tech. Digest, Transducers '93*. Pp. 124-127.

Teshigahara, A., M. Hisanaga, and T. Hattori. 1992. "Fabrication of a Shell-Body Microcar." In *Tech. Digest Vol., Third International Symposium on Micro Machine and Human Science*. Pp. 137-141.

Tsutsui, Y., N. Iwabuchi, T. Kabashima, M. Ikeda, and S. Yamashita. 1992. "Characteristics of Miniature Motor Using Thin-Film Magnet." In *Tech. Digest Vol., IEEE 2nd International Workshop on Advanced Motion Control*. Pp. 1-4.

Yasuda, T., I. Shimoyama, and H. Miura. 1993. "Microrobot Actuated by a Vibration Energy Field." In *Tech. Digest, Transducers '93*. Pp. 42-45.

CHAPTER 5

SENSOR - CIRCUIT INTEGRATION AND SYSTEM PARTITIONING

Kensall D. Wise

INTRODUCTION

The development of MEMS in the United States has been primarily lithography-based and has focused on extensions of silicon integrated circuit technology. The efforts have been rooted in electrical engineering, slowly involving more and more individuals from the mechanical engineering community. In Japan, the overall situation has been similar, although several important programs, especially those funded by MITI, have been based in mechanical engineering. As a result, these programs have emphasized nonlithographic technologies and have been somewhat less tied to silicon as a core material. The emphasis on silicon in the United States has made the integration of electronics with sensors a natural progression, and the monolithic merging of sensors, actuators, and interface circuitry has been an important focus for activities for some time. This has also been true in Japan in many companies and in a few universities, but has not been true for the remainder of the Japanese community, which has focused on other areas. This may result in more short-term payoffs from sensor-circuit integration in the United States, but also reflects less work on longer-term areas such as micromachines, for which there are really no comparable U.S. efforts yet.

The integration of interface electronics with transducers, either in monolithic or in hybrid form, is very important, as shown in Table 5.1 (Wise 1993). Integrated sensors typically produce outputs extending down to the microvolt range (limited by noise), and seek to resolve changes in resistance or capacitance of milliohms or femtofarads, or less. The output signals are continuously changing (analog) and are typically sensitive to secondary variables such as temperature, in addition to the primary parameter for which the device was intended. The zero-point outputs (offsets) and the sensitivities (slopes) are typically temperature dependent and may also be nonlinear. Worse still, the outputs at some level will vary over time. From a systems point of view, it would be preferable to deal with signals in the range of tenths of volts to volts, which are robust in the face of environmental factors such as humidity and electromagnetic noise. Since virtually all such parameters will eventually be processed by computer, the final signal should be in a digital format and any secondary-variable sensitivity (e.g., to temperature) should be eliminated along with any nonlinearity problems. Finally, there should be some way of checking the sensor in its operating system to see if the device is still giving correct data (the device should be self-testing over at least a portion of its operating range). Controlling critical industrial process equipment or invasive biomedical systems on the basis of devices that are not testable is clearly undesirable. Thus, the interface circuitry performs an essential role in any complete system.

Table 5.1
The Roles of Integrated Signal Processing Circuitry in Interfacing With Integrated Transducers and MEMS

Typical Transducer Characteristics	*SIGNAL PROCESSING CIRCUITRY*	*Desired System Characteristics*	*Challenges*
μV Signal Outputs		Volt-level Signals	Low-Noise
Parts-per-Million Changes (mΩ,fF)		Amplified, Buffered Outputs	On-Chip Analog Interface
Analog Signals		Digital Signals	In-Module ADC
Cross-Parameter Sensitivities		Pure Parameters Measured	Sensing of Secondary Variables
Individual Device Outputs		Multiplexed and Addressable	Embedded Microcontroller
Offset/Slope/ Linearity Problems		Digitally Compensated	Compensation Standards
Outputs Drift over Time		Self-Testing/ Remote Calibration	Stable References In-Module Actuators

In the past most sensors and actuators have been regarded as stand-alone components to be plugged into larger systems. However, the advantages of integrating the sensors and actuators as part of smart modules containing additional electronics are largely lost with this approach. On the other hand, adding electronics to the sensing module makes sense only if it buys increased system performance. Thus, the sensor or actuator must be considered as a system element in order to justify making it smart. This can be difficult to do in large companies and still harder when the sensors are produced as components in a different company altogether.

The need for amplification and multiplexing with sensors has been well accepted for many years, and such circuitry has been added either in monolithic or hybrid form to a great many devices. Figure 5.1 shows a progression of sensor-circuit integration beginning with a transducer having simple in-module signal conditioning (Figure 5.1a). Until recently, this signal conditioning was limited to amplification along with some temperature compensation. The output was one-way analog, with a typical range of 0 to 5 V. This signal fed into a remote analog-to-digital converter (ADC) and microcomputer and then, perhaps, to a hierarchical control system. Some sensors have evolved to the situation in Figure 5.1b, where more than one transducer is located in-module and can be addressed digitally from the processor. This has been true of some array devices and of devices with independent temperature readout. Many arrays are of the type in Figure 5.1a, however, where an on-chip or external clock serially multiplexes the various element signals to the remote processing electronics.

Figure 5.1c shows a more integrated implementation of the electronics, where the first stage of computer processing and control has been moved to the sensing/MEMS module itself (Najafi and Wise 1990). The module is now truly smart and is able to respond to various commands received externally over a digital sensor bus. It responds digitally with sensing signals that meet all of the desired system characteristics shown in Table 5.1. Using onboard memory, correction for temperature sensitivity and device nonlinearities can be done in software, allowing at least an order of magnitude improvement when compared to hardware trim techniques because of the ability to more precisely fit nonlinear response characteristics using computed polynomials or lookup tables. Such systems are not yet fully realized in the United States, although a number of companies are experimenting with them in various forms. Most involve a number of chips, assembled in hybrid form using surface mount or multichip module (MCM) technology. Within five years, however, many such modules will probably evolve to a two-chip hybrid, with a front-end sensor/actuator/MEMS chip coupled to an embedded microcontroller/microprocessor chip. With the sensing/MEMS node smart, such nodes can also operate autonomously in data gathering and self-testing, storing data in memory, perhaps doing some data interpretation, and responding rapidly to commands received over the external bus.

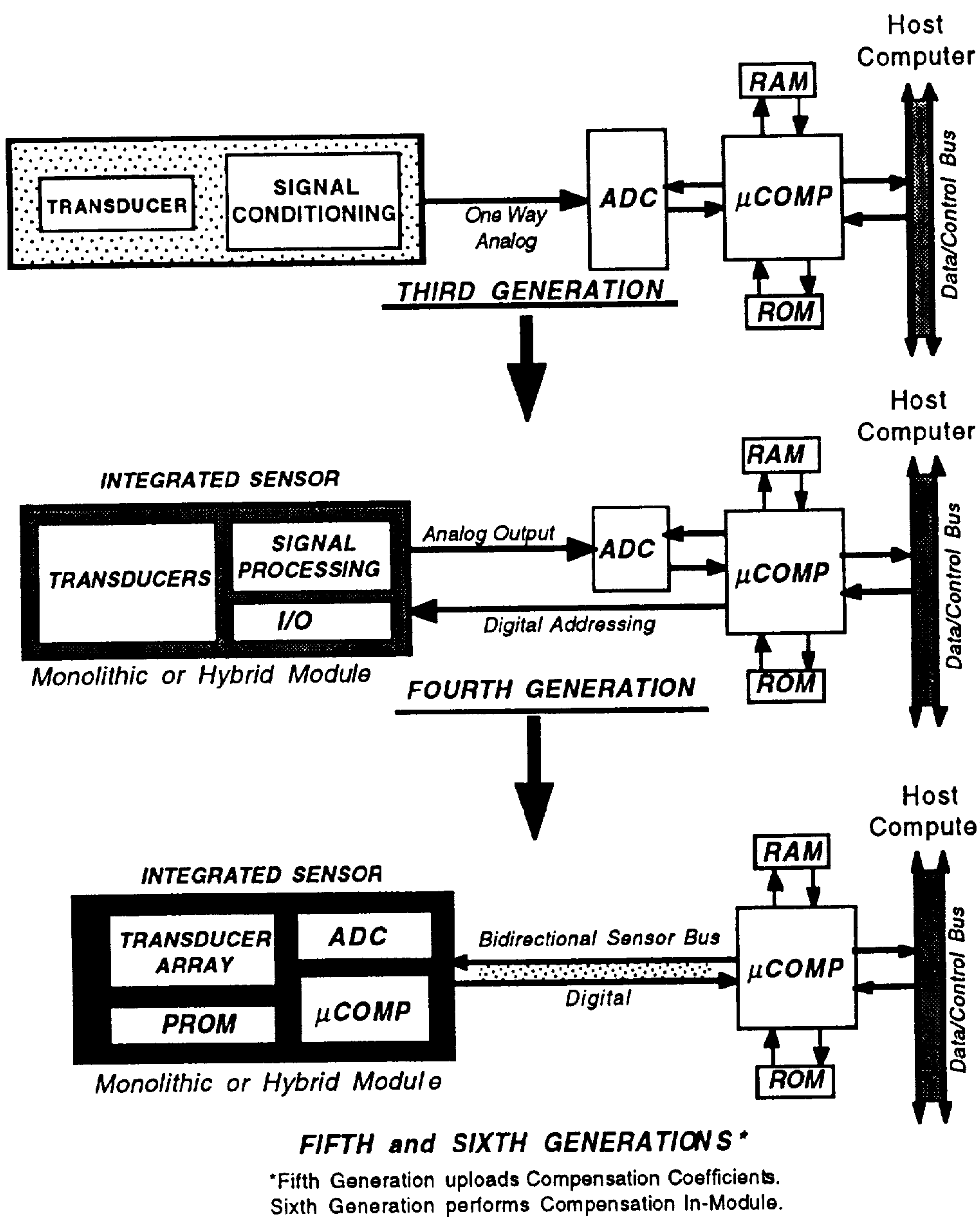


Figure 5.1. **Evolution of sensor-circuit integration and system partitioning. More electronics are being included in the sensor/MEMS module, allowing local signal processing and a digital bus output.**

As sensor-circuit integration evolves, the track depicted in Figure 5.1 appears to be evolving in several different industries in the United States. This is true in the automotive industry and in several companies involved with industrial control systems. In both cases, distributed sensing/control is required. SEMATECH is currently working on sensor bus standards for use in the semiconductor process equipment industry, and several bus standards have been proposed for automotive systems. Indeed, bus standards are an important prerequisite to this evolution since the hierarchical control system must be able to work with the sensors as integrated system elements. Avoiding the necessity of point-to-point wiring, realizing a digital output format, and obtaining greater precision are three important goals for such systems. In Japan, the situation seems to be quite similar. Of the companies visited, those involved with automotive systems (Toyota, Nippondenso) or distributed control systems (Yokogawa) were most involved with issues of sensor-circuit integration and system partitioning, whereas the more mechanically-centered organizations were not, either because they have simply chosen to emphasize a different area or because of the relatively high investments required to provide the microelectronics. Table 5.2 lists industrial sites the JTEC panel visited and identifies those thought to be particularly active in this area.

Table 5.2
Industrial Sites Visited by JTEC MEMS Panel

Matsushita Research Institute	Omron Corporation*
Yaskawa Electric	Olympus Optical Company
Canon*	Hitachi MERL
Seiko Instruments*	Mitsubishi Electric
Nippondenso Research*	Yokogawa Electric*
NTT Interdisciplinary Research*	Toyota Central R&D*

* Asterisk indicates sites where sensor-circuit integration is an important focus.

SENSOR-CIRCUIT INTEGRATION IN THE UNITED STATES

As a basis for comparison with activities in Japan, the following examples of activities in the United States illustrate the degree to which monolithic sensor-circuit integration has been employed and what it has been used for. As noted above, many U.S. efforts are still hybrid, especially in smaller companies. This approach somewhat simplifies the associated process technologies and allows the use of undisturbed circuit processes, often realized using foundries. In the United States, there is considerable interest in the establishment of MEMS foundry capabilities, with efforts at MOSIS and MCNC among the most prominent. There are no comparable efforts known in Japan. Monolithic sensor-circuit integration is being studied at several U.S. universities that have substantial circuit fabrication facilities. Sensor readout itself is also becoming an important research focus, with traditional difference amplifiers, capacitive oscillators, and switched-capacitor integrators being joined with efforts involving force-balanced feedback schemes or the use of tunneling or atomic force feedback to detect microstructure motion with extreme sensitivity.

A few representative U.S. university efforts will be described here to indicate levels of integration being achieved and functions being integrated. Figure 5.2 shows a bulk-micromachined mass flowmeter chip developed at the University of Michigan (Yoon and Wise 1992). The chip contains transducers for measuring gas flow velocity, direction, and type along with sensors for absolute temperature and pressure, allowing the computation of mass flow. On-chip CMOS circuitry allows addressable signal readout and the ability to measure the thermal time constant of the flow sensors to detect the buildup of surface films well in advance of the levels required to alter calibration. On-chip ADC is not included, but all needed readout amplifiers and servo circuits for temperature stabilization and control are. The chip size is 3.5 mm x 5 mm in 3 μm features using a simple 8-mask double-poly single-metal p-well CMOS process with five additional masks for the transducers. The on-chip actuators here are limited to the heaters used in conjunction with the flow sensors.

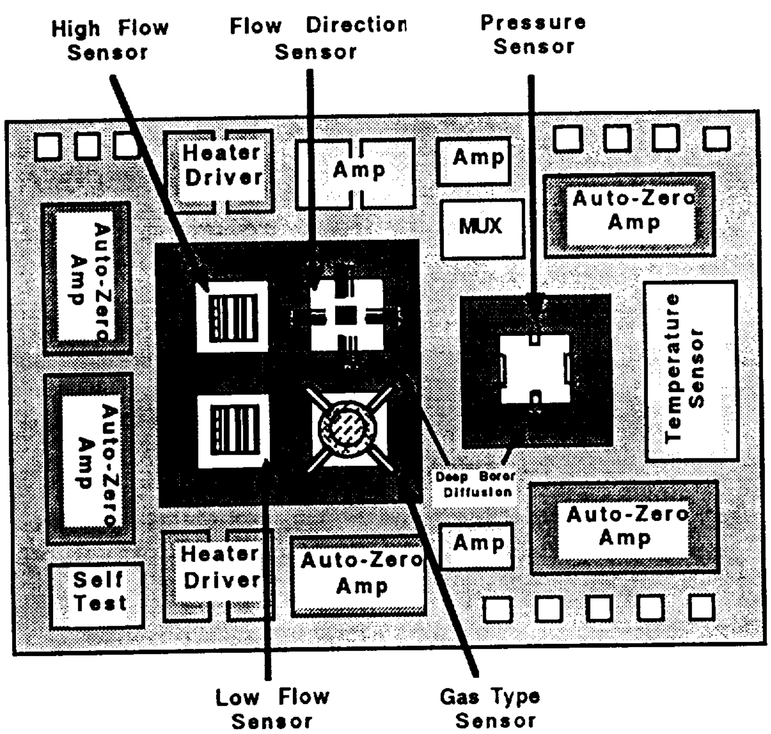


Figure 5.2. Monolithic mass flowmeter with on-chip CMOS interface circuitry.

Figure 5.3 shows a surface-micromachined high-Q microelectromechanical resonator recently realized at the University of California at Berkeley (Nguyen and Howe 1992). Electrostatic feedback is used to control the quality factor, independent of the ambient operating pressure. The chip achieves Qs of more than 50,000. Figure 5.4 shows a surface-micromachined digitally-force-balanced accelerometer with CMOS detection circuits (Yun, Howe, and Gray 1992), also developed recently at Berkeley. The chip employs a sigma-delta modulator in a feedback control loop to provide a large dynamic range and a direct digital output. The chip contains about 500 transistors in a die size of 2.5 mm x 5 mm. Still other university efforts in the United States have reached integration levels on sensor chips of several thousand devices, involving a mix of analog and digital circuit elements (Mastrangelo and Muller 1991; Tanghe and Wise 1992).

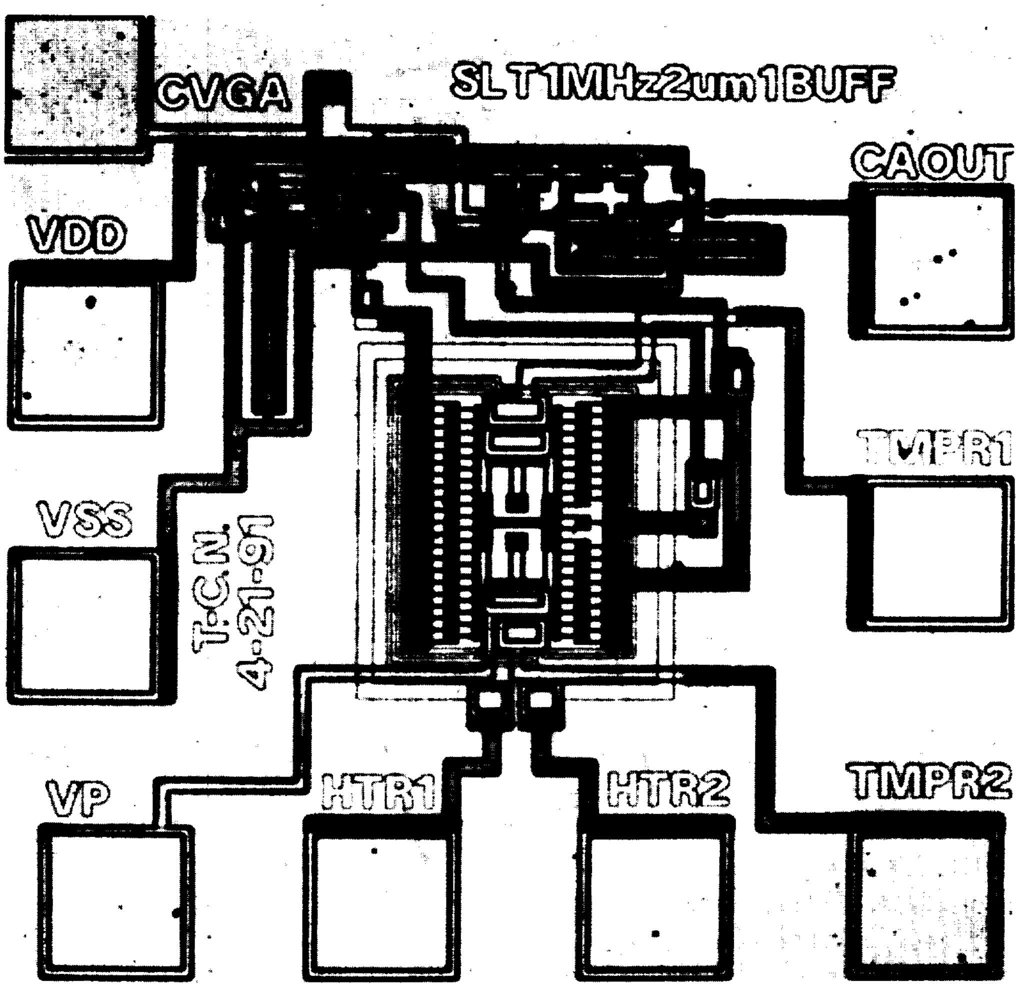


Figure 5.3. Surface-micromachined micromechanical resonator chip formed as a high-Q mechanical filter fabricated at the University of California at Berkeley.

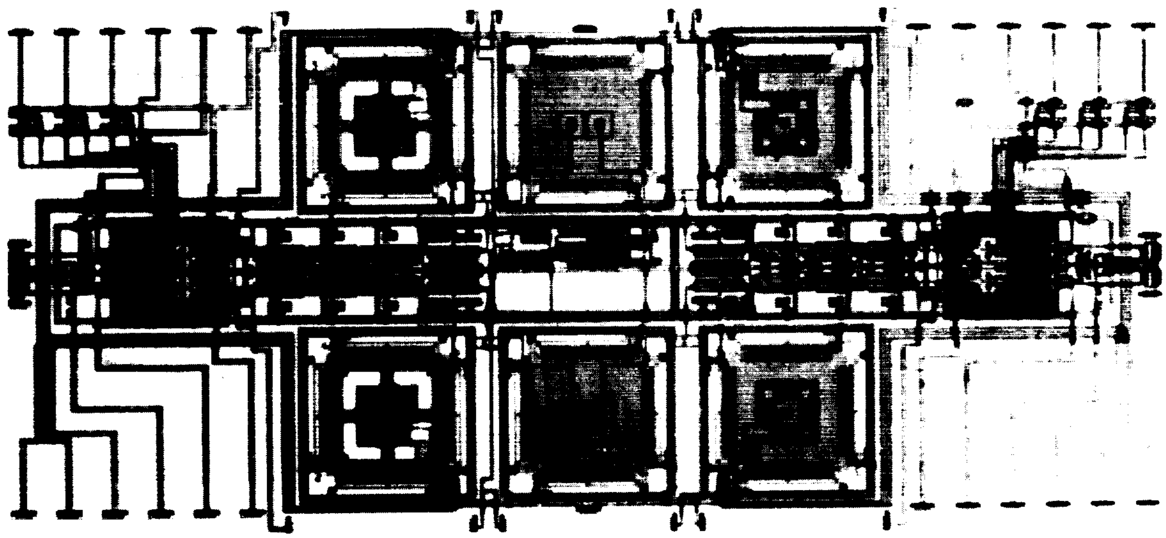


Figure 5.4. Top view of a force-balanced accelerometer chip formed by surface micromachining together with CMOS detection electronics realized at the UC Berkeley.

There are many examples of sensor-circuit integration from U.S. industry, including efforts at Ford, General Motors, Honeywell, Johnson Controls, Rosemount, Texas Instruments, Motorola, Analog Devices, and other companies. Some of these are monolithic designs and some are hybrid. Figure 5.5 shows a surface-micromachined accelerometer chip recently developed by Analog Devices (Payne and Dinsmore 1991) and intended for automotive applications. The chip contains extensive CMOS signal processing electronics, which allow the reliable detection of capacitance at the subfemtofarad level using the differential lateral capacitance between the interleaved fingers of a micromachined comb structure. Still higher levels of circuit integration have been obtained in the micromachined uncooled infrared imager reported by Honeywell (Wood, Han, and Kruse 1992) and in the micromirror-based color projection display chip (Sampsell 1993) of Texas Instruments. The devices contain arrays of over 80,000 and over 440,000 elements with monolithically-integrated selection and readout electronics. These devices represent the largest known examples of integrating transducers and electronics on a common substrate, excluding visible imagers, where integration levels of several million have been demonstrated in both the United States and in Japan. Both would be classed as MEMS devices.

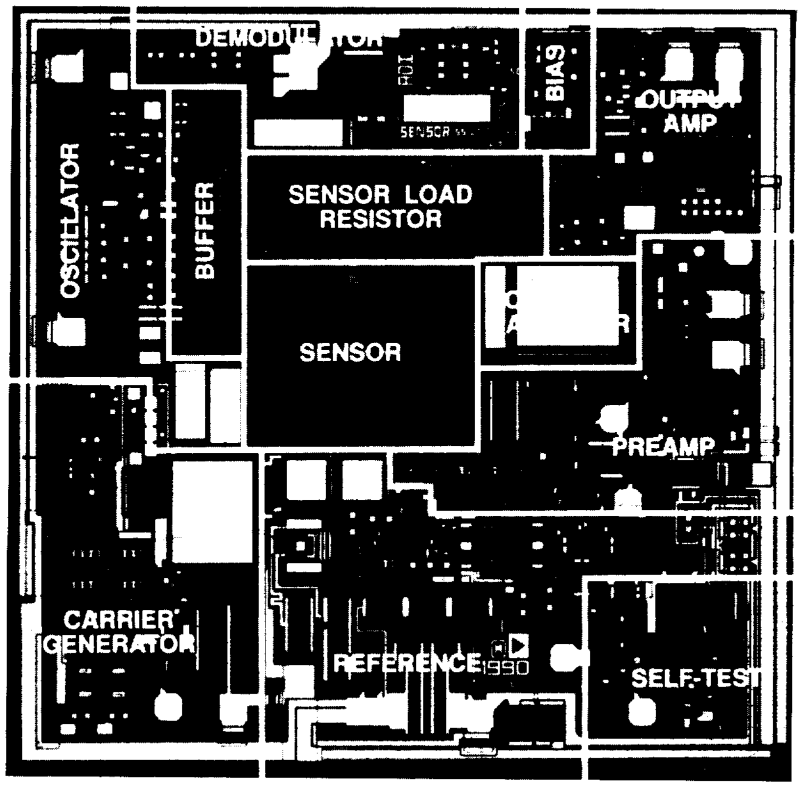


Figure 5.5. Surface-micromachined accelerometer with on-chip signal processing electronics from Analog Devices.

SENSOR-CIRCUIT INTEGRATION IN JAPAN

Most sensor-circuit integration in Japan is probably still hybrid, as it is in the United States. Researchers in Japan have been in the forefront of monolithic sensor-circuit integration for many years, however, and the push toward monolithic system implementations is continuing, especially in areas such as automotive, where volumes are high enough to recover the costs of advanced process development and where very high reliability is required. There is also considerable interest in monolithic integration for medical devices, where small overall size is a principal development goal. The situation is virtually the same in the United States. This review of efforts in Japan will revisit some of the examples used in Chapter 3, but with greater emphasis on the levels of integration involved and the circuit functions performed.

One of the first sensors with on-chip electronics was produced by Toyota in 1984 (Sugiyama et al. 1983) and is shown in Figure 5.6. It combines a piezoresistive pressure sensor with on-chip bipolar circuitry to produce outputs encoded as voltage amplitude (1 to 4 V) or frequency (210 kHz to 240 kHz) for a pressure range of 0 to 750 mmHg. The readout circuitry is used to temperature compensate the output signal to a level of less than 0.06%/°C. The chip size is 3 mm x 3.8 mm. That same year, a piezoresistive pressure sensor with on-chip electronics was also reported by Hitachi (Yamada et al. 1983).

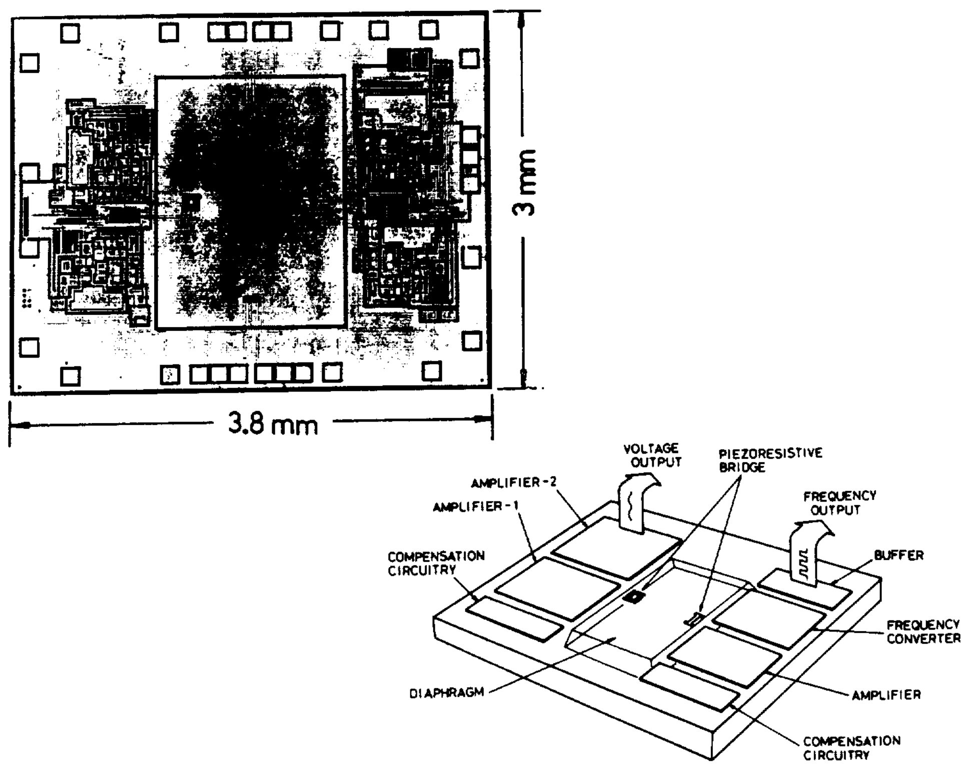


Figure 5.6. Piezoresistive pressure sensor with on-chip bipolar readout electronics reported by Toyota in 1983, one of the earliest examples of an integrated MEMS sensor with integrated electronics.

The use of on-chip electronics with pressure sensors is well illustrated in a series of papers from Toyota that were reported between 1986 and 1993. Figure 5.7 shows the diagram of a 32 x 32-element array of pressure sensors used as a tactile imager. The array is organized in x-y fashion as in a memory, each cell containing a full piezoresistive pressure sensor along with decoding electronics to allow the cell to be read out to a differential pair of analog signal leads. As first reported (Sugiyama et al. 1986), the device used a bulk micromachined cavity formed by undercutting from the front as shown in Figure 5.8. The cavity was vacuum sealed by depositing a CVD dielectric over the etch access holes; however, it was found to be difficult to get high yield from this structure due to the relatively large cavity produced and the associated production of hydrogen bubbles by the etch, which tended to become trapped due to the small access holes. More recent devices have used a surface micromachined structure, also shown in Figure 5.8, in which a thin film of sacrificial polysilicon is laterally etched away to produce the cavity. This

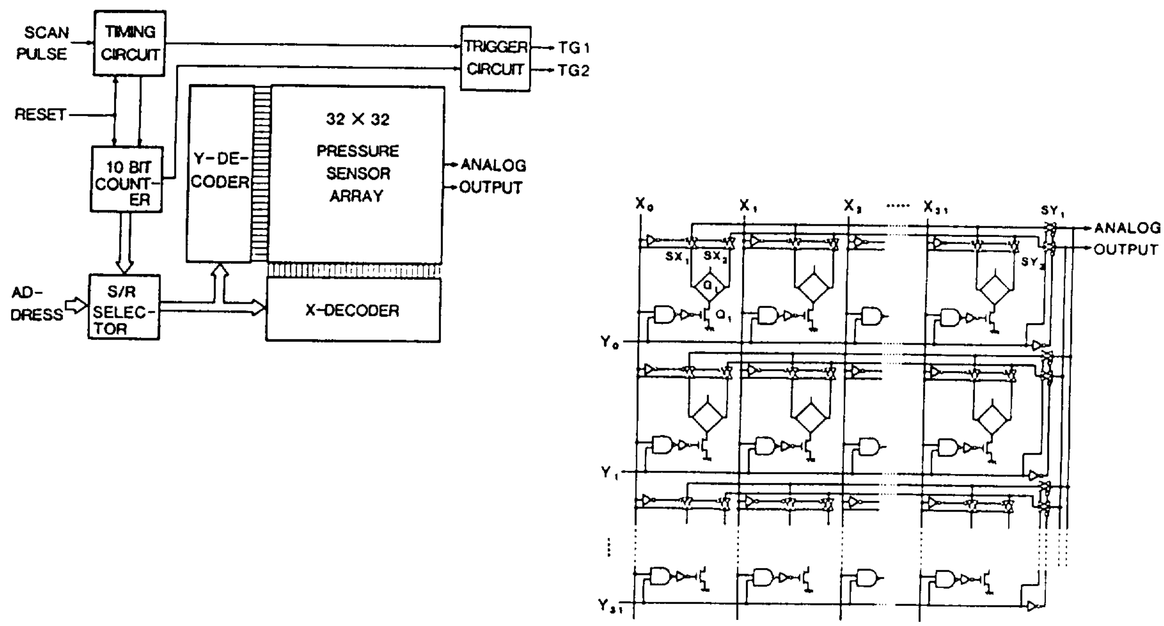


Figure 5.7. Organization of the Toyota tactile imager readout electronics. The device implements a 32 x 32-element array of pressure sensors with on-chip selection electronics. The overall die size is 10 mm x 10 mm.

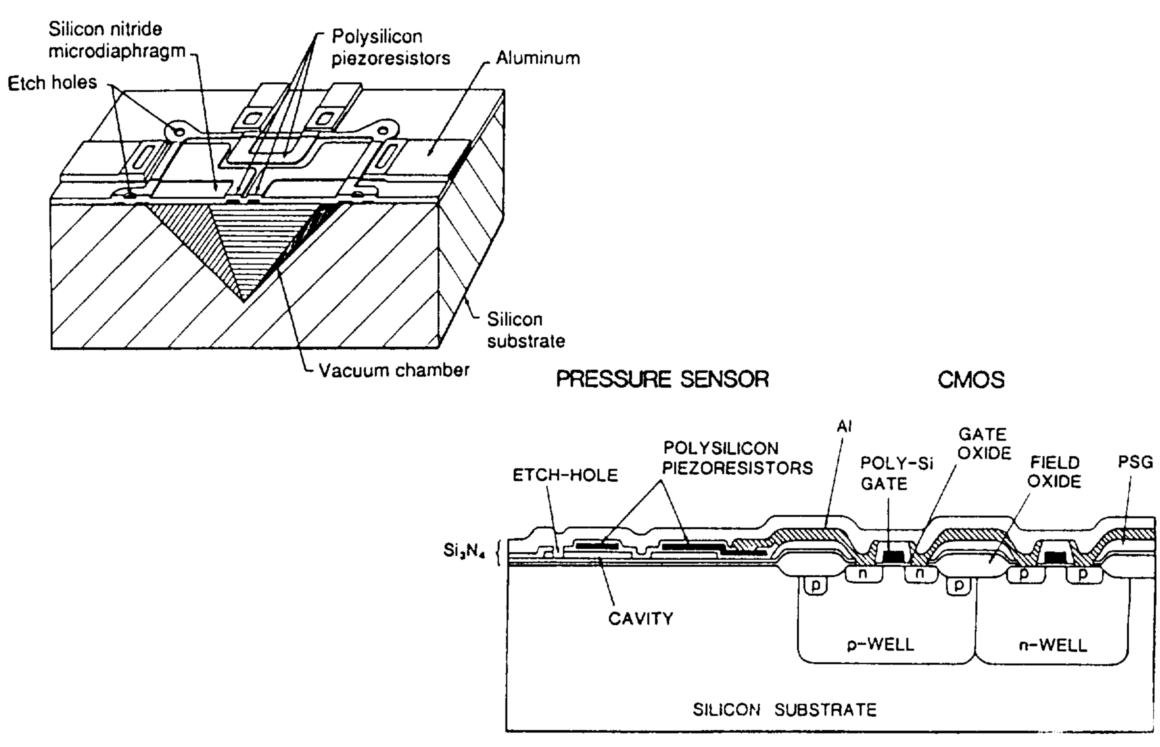


Figure 5.8. Pressure sensor evolution in the Toyota tactile imager from a bulk micromachined device (left) to a surface-micromachined structure (right). Both devices are vacuum sealed at wafer level.

produces a much shallower cavity, but also one that is higher in yield. The diaphragms are 100 μm x 100 μm in size, with a cell pitch of 250 μm and an overall chip size of 10 mm x 10 mm. The force sensitivity is about 100 mV/g-mm^2. The circuitry here is primarily utilized to provide on-chip addressing capability, and consists of about 16,000 MOS transistors, although an on-chip amplifier is also included. Similar pressure sensors (Sugiyama et al. 1986) with diaphragms 100 μm in diameter have produced a sensitivity of 10 μV/V/kPa.

Digital compensation has begun to be reported in a few efforts worldwide in which either computed polynomials (Najafi et al. 1988) are used or shift registers are loaded and used to produce analog trim voltages on-chip, using digital-to-analog converters (Hammerschmidt et al. 1993). In the former case, the compensation is done in software in the digital domain, whereas in the latter the signal path remains analog. In a recent paper, researchers at Toyoda Machine Works and Toyota have reported a digitally-compensated capacitive pressure sensor with on-chip CMOS circuitry (Nagata et al. 1992). The sensor works as a two-chip hybrid with a limited amount of electronics on the sensor and more extensive electronics on the processing chip. The sensor chip encodes the capacitance as an output frequency that is temperature compensated by adjusting the charging current of the oscillator. The span and offset are compensated using the external digital interface chip to adjust the timing window width and preset count. This approach implements compensation in the digital domain, but keeps it in hardware. The circuit organization for this device is shown in Figure 5.9.

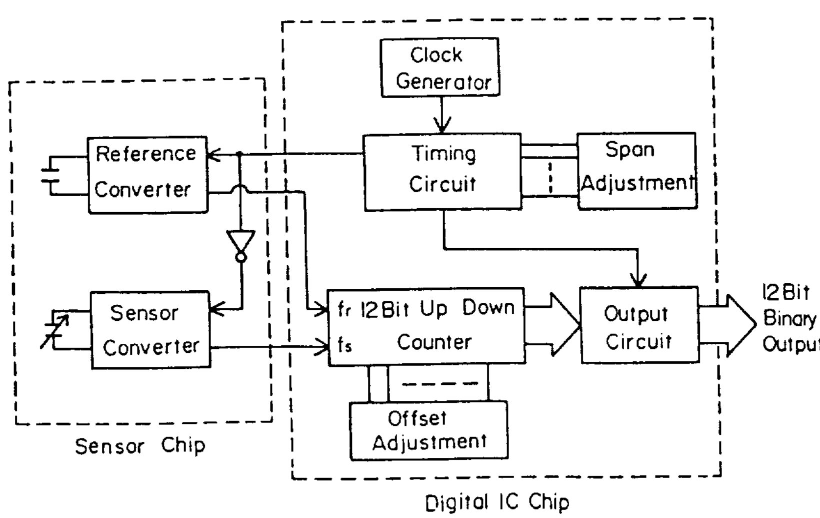


Figure 5.9. **Circuit organization in the digitally-compensated pressure sensor from Toyoda Machine Works and Toyota.**

While the Toyota activities probably represent the most aggressive efforts in Japan at monolithic sensor-circuit integration, there are several other efforts that should be mentioned. Yokogawa Electric Corporation is a leading manufacturer of instrumentation, measurement equipment, and industrial process controls. Yokogawa manufactures flowmeters, pressure sensors, power meters, valves, and many other items of interest. In the area of solid-state devices (MEMS), the company produces a piezoresistive pressure sensor and a high-performance resonant pressure sensor, the latter being of considerable interest. The DPharp pressure sensor (Ikeda et al. 1990) consists of a silicon diaphragm in which an H-shaped silicon resonator is embedded. The resonator is formed within its own vacuum-sealed cavity by a series of four selective silicon epitaxial growth steps. Figure 5.10 shows a view of an exposed beam and the process sequence used to produce it. The resonator is excited by the application of an alternating current in a DC magnetic biasing field, with a variable-gain AGC amplifier used to maintain a constant vibration amplitude, as noted in Figure 5.10. Two resonators are used, positioned on the diaphragm so that they respond differentially, increasing and decreasing their resonant frequencies as the diaphragm stress changes in response to externally applied pressure. The resonator beam is 5 μm thick and 500 μm long. Figure 5.11 shows the circuit configuration used with this device (Saigusa et al. 1992). There is no on-chip circuitry; however, a hybrid external drive chip provides the necessary drive signals. Temperature is also measured within the DPharp module, and an EPROM is used to store sensor parameters for external compensation in an accompanying converter section that contains a microprocessor. This organization, while hybrid and not yet highly integrated, is very similar to the configuration of Figure 5.1c. The DPharp is arranged to cover ranges of 0 to 400, 0 to 1,000, and 0 to 13,000 mmH_2O, meeting an accuracy specification of $\pm 0.1\%$ for each range, and with typical published errors well below this level. This device represents a state-of-the-art high-end pressure sensor, and appears to be evolving along the track shown in Figure 5.11.

Hitachi has recently (Suzuki et al. 1991) developed a bulk-micromachined force-balanced accelerometer for automotive applications that uses the feedback arrangement shown in Figure 5.12. The cantilevered accelerometer is held electrostatically in its neutral position, and the output of the device is taken as the pulse-width modulated output signal. Offset and sensitivity calibrations are implemented using a digital trimming circuit in which a ROM is programmed using the Zener-Zap technique. The accuracy is $\pm 3\%$ over a 0 to ± 1 g or 0 to ± 2 g measurement range. Again, with this device, the readout circuitry is hybrid.

Seiko Instruments produces a variety of integrated electronic devices for use in equipment ranging from consumer products (watches, portable multilingual dictionaries), information systems (thermal printers, pagers, telephone sets), and various types of production equipment. They include several small micromotors (≤ 1 cmOD, not lithography based). Seiko is clearly interested in the emerging area

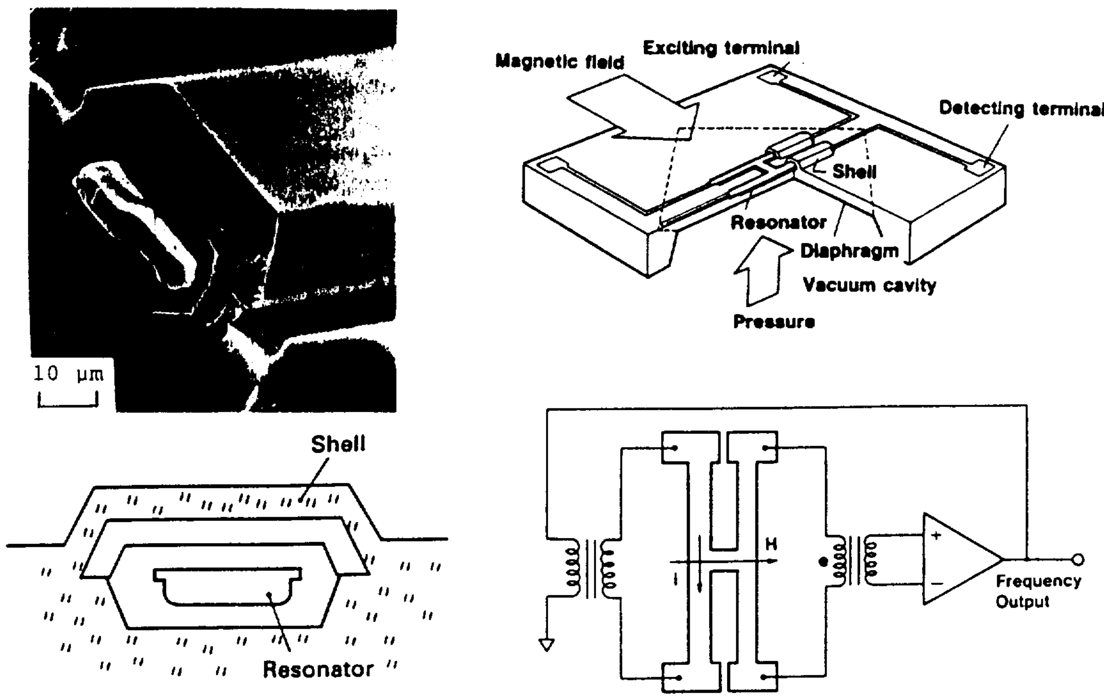


Figure 5.10. Structure and excitation scheme used for the Yokogawa DPharp resonant pressure sensor.

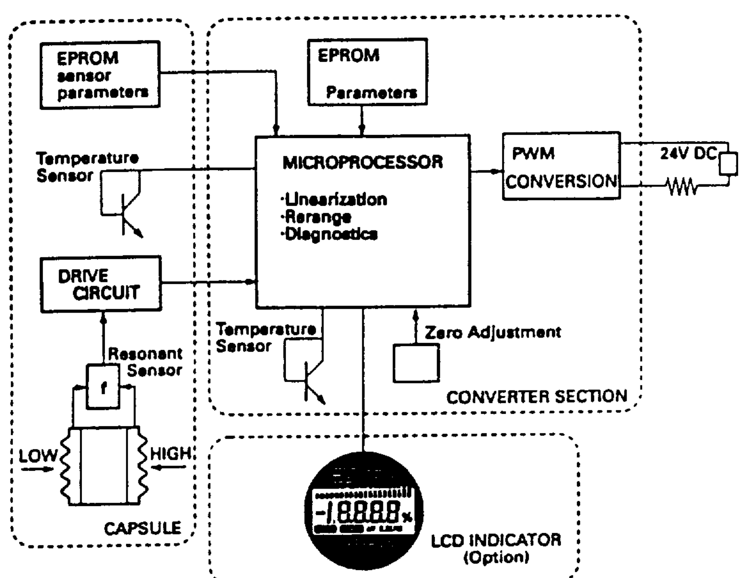


Figure 5.11. Module electronics used for signal readout and compensation in DPharp.

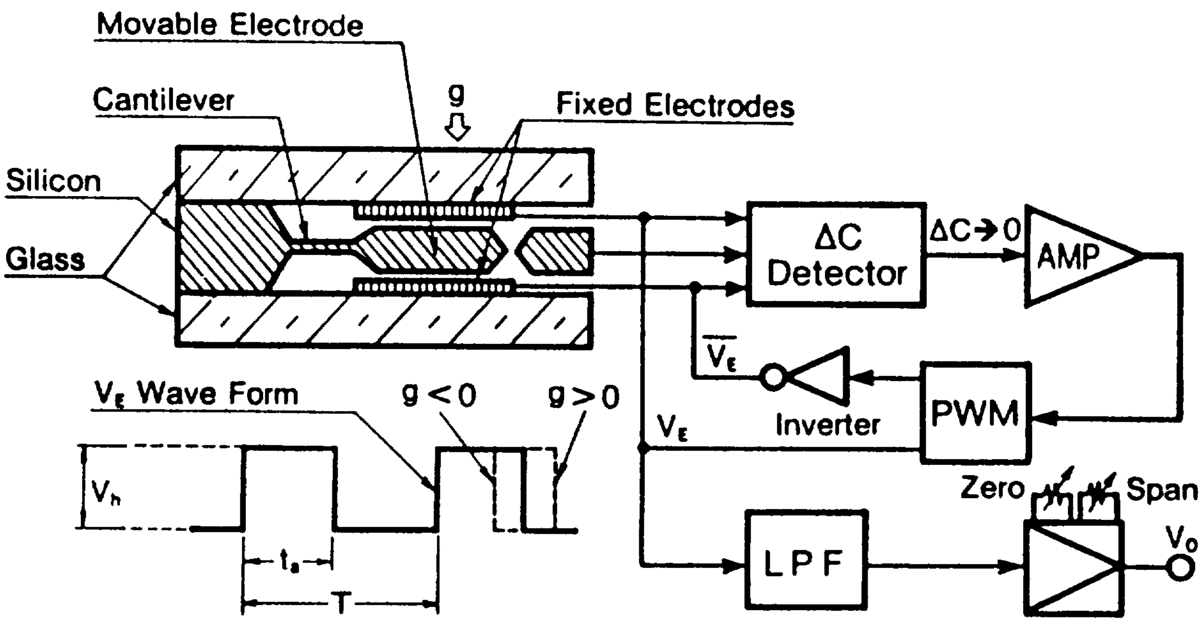


Figure 5.12. Circuit organization in the Hitachi force-balanced accelerometer.

of MEMS and possible medical products, including portable monitoring devices to allow remote patient monitoring, possibly as part of a worldwide health network. The feasibility of such systems is also being studied in the United States.

The technology levels needed to focus on sensor-circuit integration and system partitioning issues are clearly very high, making it difficult for most universities to contribute in this area. However, it is clear that significant contributions are being made at Tohoku University, which has excellent facilities for both sensor and circuit fabrication. Both capacitive pressure sensors (Matsumoto, Shoji, and Esashi 1990) and capacitive accelerometers (Matsumoto and Esashi 1992) have been reported. The pressure sensor contains a CMOS capacitance to frequency converter and is hermetically sealed using an electrostatic glass to silicon bond. The device has a nominal output frequency of 65 kHz at 760 mmHg, and a sensitivity of about -30 Hz/mmHg. The thermal offset and sensitivity drifts are about 0.05%FS/°C and 0.09%FS/°C, respectively, with a long-term drift of ±2 mmHg/week. The capacitive accelerometer is based on a silicon proof mass suspended by bulk undercut beams.

An on-chip phase-locked loop circuit is used for force-balancing. The force-sensitivity is 200 Hz/g, with a nominal output frequency of 70 kHz. The integration levels on both of these chips is modest, probably consisting of less than 100 transistors; however, with the process established, the integration level could be easily pushed higher if desired.

ISSUES IN SENSOR-CIRCUIT INTEGRATION

As noted above, it is evident that there is considerable effort directed at sensor-circuit integration in Japan, especially in connection with automotive and medical applications. Automotive is the current principal driver, with medical a possible emerging force during the coming decade. The evolution to "instruments on a chip" is viewed in Japan as likely in the longer term, with nearer-term efforts probably limited to sensing systems and actuators used primarily in connection with the sensors (as in force-balanced accelerometer structures and thermally-based flowmeters). The combination of sensors, actuators, and electronics to do control is viewed as most likely to proceed first in optical devices, due to the compatibility of such systems with hermetic packaging and low drive forces. Both of these viewpoints seem much in line with thinking in the United States.

The JTEC panel's Japanese hosts expressed the view that systems will be primarily hybrid at first, evolving slowly to monolithic implementations as power levels and device process sequences permit. The elimination of parasitics was viewed as a significant motivation for monolithic devices, with integration levels expected to remain modest (less than a few thousand devices) during the remainder of this decade. Embedded microcontrollers were viewed as very likely in high-end devices (and indeed are already present in devices such as the DPharp), migrating into low-end devices as cost allows. It was noted that such devices may be required in order to achieve compatibility with distributed bus-organized systems. Bus standards were viewed as important and likely for automotive applications, but do not seem to be a significant focus yet for other areas.

The question of sensor calibration is clearly one being pursued through a number of approaches, both in hardware and software, and no clear preferences were evident in the JTEC site visits. Some researchers felt that calibration/compensation was better done in hardware, and that the issue was either not very important or not a significant effort in MEMS. Others felt that it was an important issue, particularly with regard to system partitioning, and that it was likely to be done in software in the future. It is expected that industry will converge around a few standard MEMS processes (or at least this seems to be a desirable goal), and that this will be determined in part by the way systems are partitioned in the future.

CONCLUSIONS

In terms of sensor-circuit integration, many systems in both the United States and Japan are being implemented using hybrid electronics. Trends favor monolithic integration in high-volume applications and in those where reliability and/or size are especially critical factors. It is noteworthy that there was considerable interest in medical applications at many Japanese sites -- much more than is found in the United States, where worries over liability issues and long development/testing cycles cause most companies to avoid the area and are currently causing some established companies to leave it. The markets here are large, and Japan seems to be well positioned to go after them aggressively. Levels of integration in Japan are comparable to those in the United States, although there are probably more places in the United States where integration levels are significant. University facilities are generally limited, so that there is relatively less effort devoted to these issues in academia in Japan as compared with the United States. As noted above, Tohoku University, an exception in this regard, is making solid contributions. Efforts on digital compensation, self testing, and sensor bus standards are still in relatively early stages, but clearly these are areas that will see growing emphasis in the future.

Overall, the United States is certainly competitive with Japan in the sensor-circuit integration area. The worldwide cooperation occurring in sensors and MEMS ensures that development trends are similar and tends to unify approaches as well as the problems being addressed.

REFERENCES

Hammerschmidt, D., F.V. Schnatz, W. Brockherde, B.J. Hosticka, and E. Obermeier. 1993. "A CMOS Piezoresistive Pressure Sensor with On-Chip Programming and Calibration." In *Digest 1993 IEEE International Solid-State Circuits Conf.*, Pp. 128-129.

Ikeda, K., H. Kuwayama, T. Kobayashi, T. Watanabe, T. Nishikawa, T. Yoshida, and K. Harada. 1990. "Silicon Pressure Sensor Integrates Resonant Strain Gauge on Diaphragm." *Sensors and Actuators.* A21-A23: 146-150.

Mastrangelo, C., and R.S. Muller. 1991. "Thermal Absolute-Pressure Sensor with On-Chip Digital Front-End." In *Digest IEEE Int. Solid-State Circuits Conf.* Pp. 188-189.

Matsumoto, Y., S. Shoji, and M. Esashi. 1990. "A Miniature Integrated Capacitive Pressure Sensor." In *Conf. on Solid-State Devices and Materials.* Pp. 701-704.

Matsumoto, Y., and M. Esashi. 1992. "Integrated Capacitive Accelerometer with Novel Electrostatic Force Balancing." In *Digest 11th Sensor Symposium*, pp. 47-50.

Nagata, T., H. Terabe, S. Kuwahara, S. Sakurai, O. Tabata, S. Sugiyama, and M. Esashi. 1992. "Digital Compensated Capacitive Pressure Sensor Using CMOS Technology for Low-Pressure Measurements." *Sensors and Actuators.* A34: 173-177.

Najafi, N., K.W. Clayton, W. Baer, K. Najafi, and K.D. Wise. 1988. "An Architecture and Interface for VLSI Sensors." In *Digest IEEE Solid-State Sensor Workshop.* Pp. 76-79.

Najafi, N., and K.D. Wise. 1990. "An Organization and Interface for Sensor-Driven Semiconductor Process Control Systems." *IEEE Journal of Semiconductor Manufacturing.* November: 230-238.

Nguyen, C.T.-C., and R. Howe. 1992. "Quality-Factor Control for Micromechanical Resonators." In *Digest Int. Electron Devices Meeting.* Pp. 505-508.

Payne, R.S. and K.A. Dinsmore. 1991. "Surface Micromachined Accelerometer: A Technology Update." In *Digest SAE Meeting.* Pp. 127-135.

Saigusa, T., H. Kuwayama, S. Gotoh, and M. Yamagata. 1992. "The DPharp Series Electronic Differential Pressure Transmitters." *Yokogawa Technical Report.* English Edition, 15: 30-37.

Sampsell, J.B. 1993. "The Digital Micromirror Device and Its Application to Projection Displays." In *Digest, International Conference on Solid-State Sensors and Actuators.* Pp. 24-27.

Sugiyama, S., M. Takigawa, and I. Igarashi. 1983. "Integrated Piezoresistive Pressure Sensor with both Voltage and Frequency Output." *Sensors and Actuators.* 4, September: 113-120.

Sugiyama, S., K. Shimaoka, and O. Tabata. 1993. "Surface-Micromachined Microdiaphragm Pressure Sensors." *Sensors and Materials.* 4: 265-275.

Sugiyama, S., T. Suzuki, K. Kawahata, K. Shimaoka, M. Takigawa, and I. Igarashi. 1986. "Micro-Diaphragm Pressure Sensor." In *Technical Digest, International Electron Devices Meeting.* Pp. 184-187.

Sugiyama, S., K. Kawahata, M. Yoneda, and I. Igarashi. 1990. "Tactile Image Detection Using a 1K-Element Silicon Pressure Sensor Array." *Sensors and Actuators.* A21-23: 397-400.

Suzuki, S., S. Tsuchitani, K. Sato, S. Naito, S. Ueno, M. Suzuki, N. Ichikawa, and M. Sato. 1991. "Semiconductor Capacitance-Type Accelerometer with PWM Electrostatic Servo Technique." Paper number 910274. SAE International Congress. Detroit.

Tanghe, S.J., and K.D. Wise. 1992. "A 16-Channel Neural Stimulating Array." In *Digest IEEE International Solid-State Circuits Conference*. Pp. 128-129.

Wise, K.D. 1993. "Integrated Microinstrumentation Systems: Smart Peripherals for Distributed Sensing and Control." In *Digest 1993 IEEE International Solid-State Circuits Conference*. Pp. 126-127.

Wood, R.A., C.J. Han, and P.W. Kruse. 1992. "Integrated Uncooled Infrared Detector Imaging Arrays." In *Digest IEEE Solid-State Sensor and Actuator Workshop*. Pp. 132-135.

Yamada, K., M. Nishihara, R. Kanzawa, and R. Kobayashi. 1992. "A Piezoresistive Integrated Pressure Sensor." *Sensors and Actuators*. 4, September: 63-69.

Yoon, E., and K.D. Wise. 1992. "An Integrated Mass Flow Sensor with On-Chip CMOS Interface Circuitry." *IEEE Trans. on Electron Devices*. 39, June: 1376-1386.

Yun, W., R.T. Howe, and P.R. Gray. 1992. "Surface Micromachined Digitally Force-Balanced Accelerometer with Integrated CMOS Detection Circuitry." In *Digest IEEE Solid-State Sensor and Actuator Workshop*. Pp. 126-129.

CHAPTER 6

PACKAGING, ASSEMBLY, AND TESTING

Stephen C. Jacobsen

INTRODUCTION TO PAT AND ITS RELATIONSHIP TO MEMS

Importance of PAT

Clearly the achievement of many of the characteristics planned for MEMS-based systems will depend primarily on the physical performance of internal elements. However, especially with this new class of microbased subsystems, additional problems related to packaging, assembly, and testing (PAT) must be overcome before success is achieved with commercial products. In fact, packaging, assembly, and testing issues now loom as substantial barriers to the practical integration, and subsequent commercialization, of a large body of developments being generated in MEMS-related R&D and business communities.

Packaging of MEMS devices is more complicated than in the case of electronic or mechanical ancestors of microdevices. Since new sensors and actuators must physically interact with the environment, packages require pass-throughs for transmission of fields, photons, fluids, moving shafts, chemicals, and so forth. The integration of subsystems and components into complete products will require the development of new housings, conduits, connectors, seals, manufacturing approaches, structures, and central controllers.

It is probably true that PAT processes will dominate the economics of final products as well as substantially determine factors related to ruggedness, reliability, and maintainability. Fortunately, many new processes (or old processes modified for use in smaller applications) such as those listed in Table 6.1 are being developed and will be available for use in PAT. Also, such centralized fabrication facilities as MCNC are emerging, and express interest not only in fundamental fabrication processes, but also in providing packaging services.

Table 6.1
Fabrication Processes

Etching	Isotropic	Anisotropic	Dopant Stop	
Lithography	Photo	E-beam	X Ray	
Thin Film Deposit	Sputtering	CVDP	Vapor Dep.	
Electrosurfacing	Anodizing	Plating	Polishing	
Characterization	Profilometer	Interference	STM	ATM
Microcutting	Laser	E-beam	EDM	
Wire Bonding	Ultrasonic	Compression	Soldering	Brazing
Bonding	Adhesives	Thermal	Friction	
Surface Processing	Ion Milling	Diffusion		EDM
Welding	Laser	E-beam	Spot	
Coating	Resist	Dipping	Powder	
Extrusion	T	Coextrusion		
Forming	Hydro	Stamping	Drawing	
Joining	Riveting	Screwing	Contact	
Lapping	Planar	Spherical		
Machining	Turning	Milling	Drilling	
Molding	Injection	Vacuum	Casting	
Molding	Compression	Dipping		
Removal	Grinding	Polishing	Etching	
Lithography	Planar	Nonplanar	Stereo	
Welding	Gas	TIG	Arc	

Acquiring Information on PAT Processes

Acquiring information about PAT activities during the JTEC trip was a difficult task for a number of reasons. (It should be mentioned here that obtaining similar information in the United States or Europe would have been equally difficult.) First, PAT methods are not long-term developments, but relate to the important three-year window that renders them critical to the commercial performance of a product in the marketplace. Since patents in the PAT area are less fundamental, their legal status is less secure, and secrecy is the mechanism for maintaining competitive advantage. Second, PAT is application specific. MEMS devices include small, embedded, interconnected, fragile elements, the assembly and evaluation of which is unique to the specific device being produced. Therefore, it is difficult to discuss MEMS-PAT in a brief fashion based on fundamental first principles. Third, with respect to emerging MEMS-based systems, PAT technology is so new that in many cases there is nothing to discuss because the technology has simply not developed yet. Fourth, since PAT processes are evolving rapidly, the language and structure necessary to discuss issues completely is just emerging.

In the following sections, PAT methods will be discussed in terms of four systems levels and in terms of levels of packaging that range from closed-rigid to open-exposed.

PAT PROCESSES OCCUR AT ALL FOUR SYSTEMS LEVELS

Level 1: Microelectronics

Fabrication processes that produce chips for electronic-only functions use repetitive masking-deposition-removal processes to generate multiple layers of thin patterned materials functioning together as interconnected transistors, conductors and other circuit elements. The circuit layers, fabricated directly on silicon wafers, are separated into individual chips that are tested, combined with other circuit elements, and then assembled into packages. The drive for greater levels of integration in chip-based electronic circuits has pushed the development of lithographic fabrication processes to impressive levels, especially with regard to the achievement of finer resolution, higher speed, better efficiency, and tighter process control for improvement in yield.

Developments in the areas of packaging, assembly, and testing, while also impressive, have been less expansive. They have been focused on placing one or many chips in rigid, hermetically-sealed housings with focus primarily on economy and thermal control. Sealed package lead-throughs provide only electrical connection between the chip and the outside world for assembly into larger systems and after-packaging testing. Typical electronic packages are shown in Figure 6.1.

New systems, planned for the near future, will require subsystems that include not only electronic functions but others, such as mechanical, thermal, chemical, and optical. The new systems will include moving parts and require the passage of other-than-electric information through package walls. New systems will also include other requirements, such as nonplanar geometries, operation in more harsh environments, and other nonstandard characteristics.

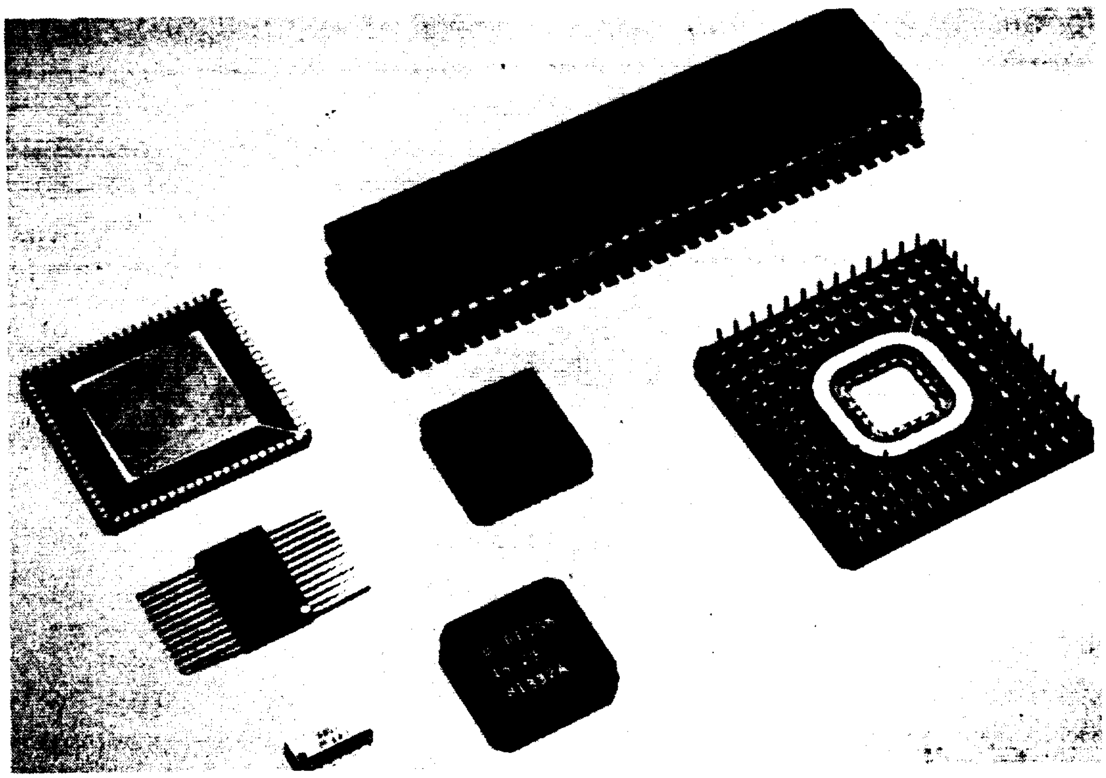


Figure 6.1. A variety of typical closed, rigid electronic packages: dual in-line package (DIP), pin grid array (PGA), surface mounts, direct die mounting (from H.B. Bakoglu, *Circuits, Interconnections and Packaging for VLSI*, Reading, MA: Addison Wesley, 1990).

Level 2: Micromechanics

The micromechanics area has evolved, mainly over the past decade, with a focus on creating thicker, void-containing microassemblies which, in addition to electronics, include moving parts and utilize other physical processes, such as mechanical, optical, fluid, thermal, chemical, nuclear, and so on. Microassemblies targeted for development include subelements such as: (1) rigid shapes that form open or closed channels, coils to produce magnetic fields, orifices, large area capacitors; (2) structures that move by flexing, such as diaphragms, flexures, and springs; and (3) assemblies that permit relative motion (sliding) between elements such as links, valves, hinges, gears, and sliders. Figures in Chapters 2 and 5 of this report provide excellent examples of sacrificial layer etch-based techniques used to form complex geometry structures.

Microassemblies are interesting because they make possible the creation of microsubsystems which can be classified as sensors, actuators, and subsystems (SAS). SAS can be arranged to form components that function to enhance the performance, reliability, and economy of the larger systems in which they will function. Of particular importance will be the generation of SAS with high performance and reliability, small size, efficient intercommunication capability, local intelligence, and low cost. Present SAS development projects are investigating large numbers of materials and processes in which reciprocal energy-movement relationships exist (energy to movement or movement to energy). Approaches used include phenomena such as: magnetic fields, electrostatic fields, electrostrictive properties, magnetostrictive effects, piezoelectric bimorphs, thermal expansion elements, shape memory alloys, phase transition liquids and solids, impact systems, chemical reactions, and polymeric materials.

Other sections of this report show good examples of micromachines formed by various silicon micromachining processes. Other figures illustrate: (1) the formation of moving elements, such as comb drives or accelerometer masses, suspended by flexures; (2) revolute joints suspending micromotor rotor; (3) actuated microcantilever beams, and others.

Level 3: Microelectromechanical Systems

MEMS is an emerging field focused on the integration of microelectronics and micromechanics to form systems of intercommunicating sensors, actuators, and subsystems that can be integrated to form components. The components can then function as the interconnected building blocks necessary for realization of systems based on new machine architectures that use larger numbers of sensors and actuators together with distributed subcontrollers.

The design and fabrication of MEMS-based systems is a complex undertaking. New mentalities, processes, and fabrication approaches are required, and even the act of requirements-definition is difficult. For example, just a few characteristics required for the specification of any real sensor include sensitivity, resolution, stability, dynamic range, bandwidth, drift, noise, reliability, ruggedness, addressability, cost, size, weight, absolute or incremental output, update rate, power consumption, local intelligence, output information architecture, life, stiction, backlash, required support systems, and so forth. Another example of just a few characteristics required for the specification of any real actuator include output force or torque, output speed, output impedance (stiffness, damping, inertia), input (voltage, pressure, current, flow, etc.) reversibility, efficiency, size, weight, stiction, backlash, thermal tolerance, reliability, ruggedness, emissions, cost, life, power dissipation, life, leakage, required support systems, and so forth.

The MEMS area is important because MEMS-based approaches can produce products with fundamental advantages in performance, reliability, and economy. MEMS-based systems can: (1) be used in many existing applications such that natural commercial motivations will push development, and (2) generate previously nonexistent systems that address important international priorities. Figure 6.2 shows a good example of a MEMS-based optical system (Texas Instruments), which includes numerous actuated micromirrors systematically driven to generate a color display. The optical display is packaged in a rigid-closed housing with a transparent optical pass-through for light passage to and from mirrors. Assembly at the microlevel is achieved by integrated, hands-off, techniques. Assembly of the chip into the package is achieved via conventional methods. Testing for individual pixel performance is achieved by examining dynamic image quality.

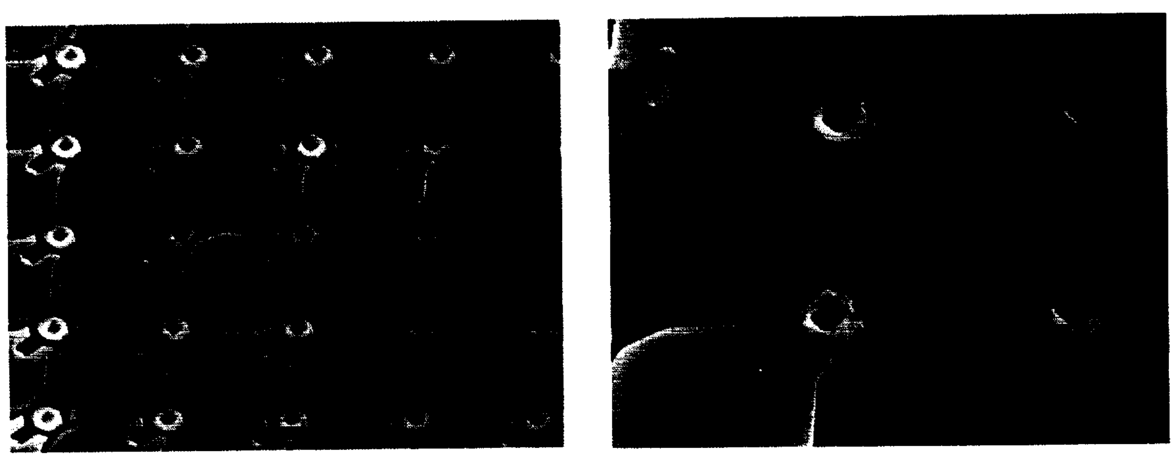


Figure 6.2. A MEMS-based array of actuated micromirrors (Texas Instruments).

Figure 6.3 shows a method of vacuum packaging by glass-silicon anodic bonding, which is being developed by Henmi, Shoji, Yoshimi, and Esashi at Tohoku University. Such methods will be used in the future to permit closed-rigid or closed-flexible packaging to occur at a more integrated process level.

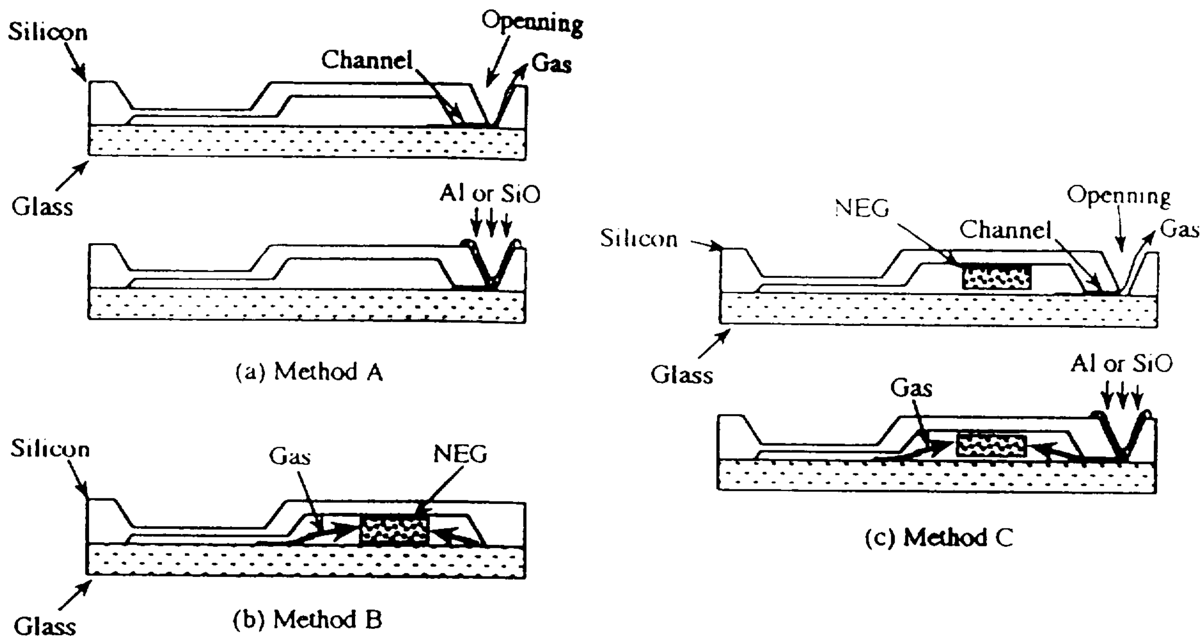


Figure 6.3. A method of integrated vacuum packaging.

Level 4: Complete Systems

Complete systems can be formed by integrating elements from microelectronic, micromachine, and MEMS levels. In many cases the elements function as discriminating subsystems that permit a product to achieve properties not otherwise possible. It should not be forgotten that, in many cases, PAT consists of very important drivers of system reliability, ruggedness, maintainability, and cost. Good examples of complete systems are shown in Figures 6.4 through 6.7.

Figure 6.4 shows a cross section of a typical, Japanese-produced SLR camera. A typical system includes macromechanics, microelectronics, optics, sensors, very small actuators, seals, many input controls, internal intelligence, electric pass-throughs, and other elements. The modern camera, now typically taken for granted, represents a series of triumphs in both macro- and micro-PAT, in terms of reliability, ruggedness, and cost.

Figures 6.5 and 6.6 show two projects proposed by the Micromachine Center and supported by the Ministry of International Trade and Industry (MITI). The projects focus on "the development of micromachine technology, and to encourage a central

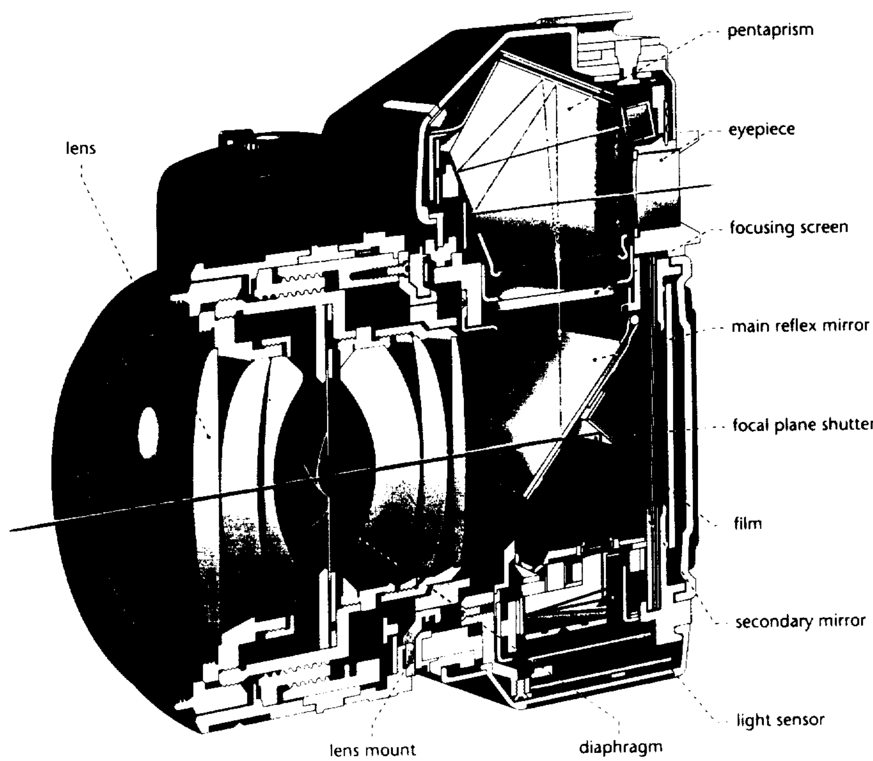


Figure 6.4. Cross section of a typical Japanese-produced SLR camera.

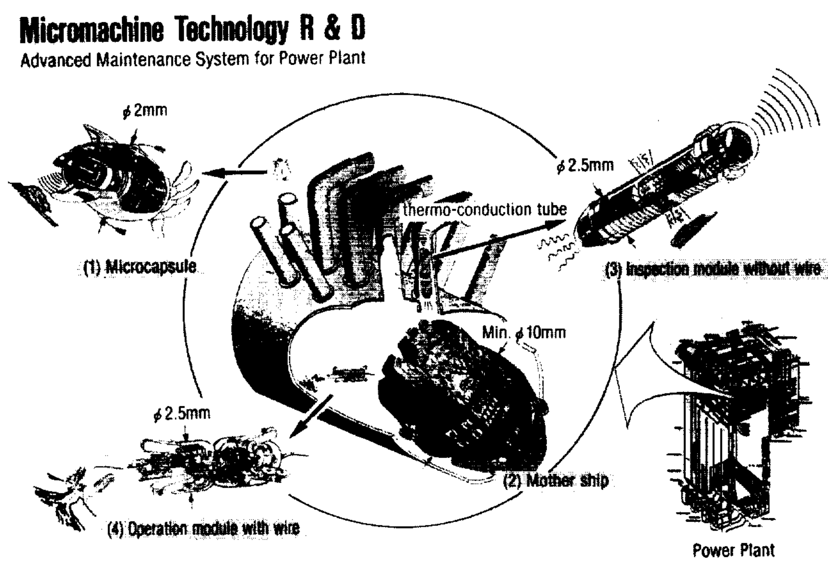


Figure 6.5. Concept for an advanced maintenance system for a power plant (MITI).

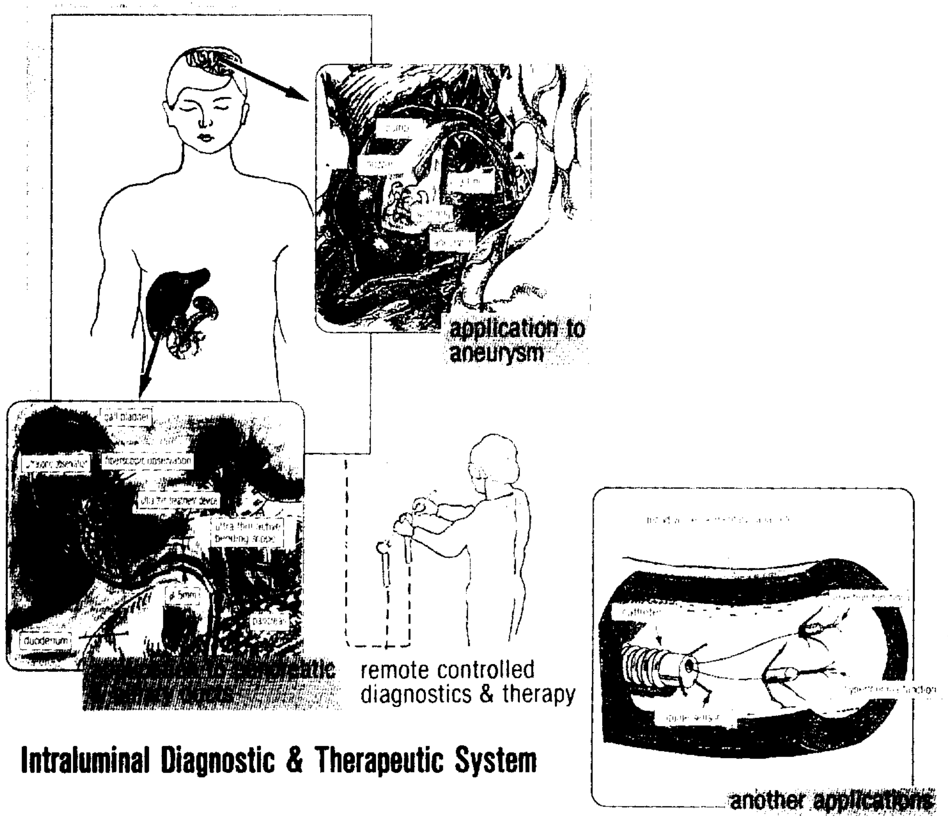


Figure 6.6. Concept for an intraluminal diagnostic and therapeutic system (MITI).

role for these machines as they spread into various economic and social sectors." The projects are based on the idea that "micromachine technology must be established and steps taken to promote information exchange in this field." MITI plans that the projects will contribute both to development of domestic Japanese industry and to the international community. Figure 6.5 illustrates the concept for subsystems that can provide distributed, internal power plant maintenance. Figure 6.6 shows the concept for an intraluminal diagnostic and therapeutic system. Both projects are designed to promote developments in microelectronics, micromechanics, and MEMS. They will also require broad-based developments in PAT if any success is to be achieved. See Chapter 7 and the MITI site report for further information.

Figure 6.7 shows a duodenofiberscope currently marketed by Olympus. The system is a good example of current technology in systems for the execution of less invasive medical procedures. The scope shown is a commercial system (10 mm diameter with internal cannula pathways of 2.2 mm diameter). Emerging systems, not shown to the JTEC team, will achieve smaller sizes (1 to 2 mm diameters), which will intensify the need for MEMS-based systems for the tip. In general, scopes or catheters are introduced at an orifice and translated to a site in order to introduce or withdraw fluids, take biopsies, sense, view, treat, cut, expand, cauterize or otherwise interact with small, remote, anatomic features or lesions within a body. Although not themselves microsystems, endoscopes and catheters provide an excellent base for the application of microsystems on their tips. Here again, microsystems will provide discriminating features, but PAT-related issues, both macro and micro, will determine achievable levels of system reliability, ruggedness, and cost.

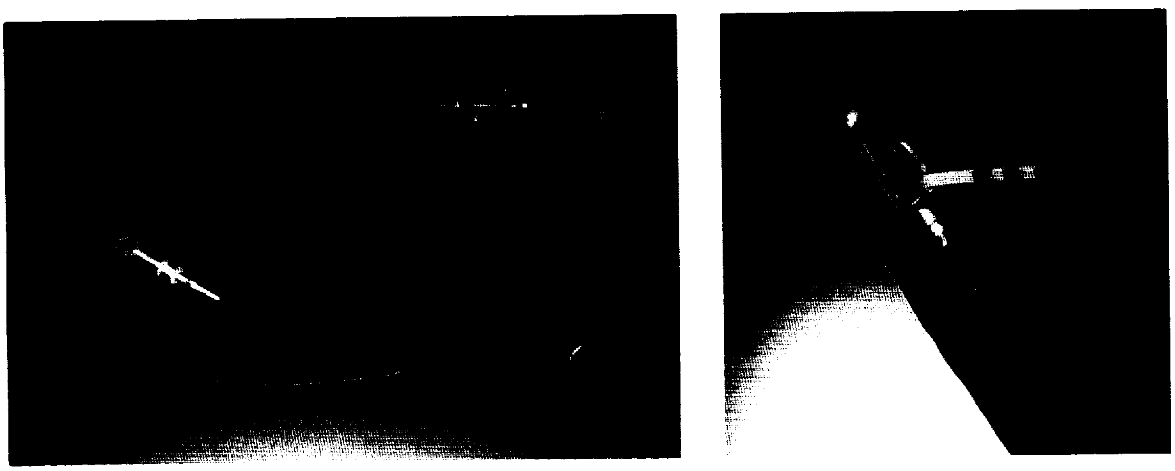


Figure 6.7. Duodenofiberscope currently marketed by Olympus.

REVIEW OF PACKAGING, ASSEMBLY, AND TESTING

Package Definitions, Requirements, and Design

A typical electrical subsystem package includes: (1) core devices, such as chips and wires; (2) housings, which include mounting points; (3) electrical connections and pass-throughs; (4) covers, which provide access and then sealing after closure; and (5) external features for mechanical attachment and thermal transfer. New packages for MEMS-based subsystems will also include unique, sometimes multichannel, other-than-electrical pass-throughs for mechanical, optical, fluid, thermal, chemical, and nuclear energy transfer. Systems of components that are based on SAS subsystems will also require additional packaging innovations related to information buses or other means of communication, less obtrusive fixation methods, local information processing nodes, and others specific to networked systems. Innovative assembly and testing procedures will be necessary to complete the manufacture of new products.

The definition of package requirements is also a complex process. Just a few necessary features include: geometry (size, shape, attachment), abuse tolerance (vibration, impact, acceleration), interconnection methods (regime, density, dynamics, delay), thermal (isolation, temperature range, control), life (maintenance requirements, fatigue, operational range), chemical effects (corrosion, intrusion), shielding (RF, nuclear, thermal), and economy (original and life cycle cost).

For these discussions, Figure 6.8 will be used to indicate areas of effort for PAT. The figure includes a review of procedures in terms of fabrication processes, packaging, assembly, and testing. Procedures are applied along the progression of systems from subsystems to components to complete systems. Note that in each area tests might be required to validate manufacturing success. Note also that the design of new PAT systems will be an integral part of the overall system design. Greater attention to analysis, modeling, simulation, and subtesting will be necessary.

PROCEDURE / LEVEL	Subcomponent	Component	System
Fabrication Process	PAT-fpsc	PAT-fpc	PAT-fps
Package	PAT-psc	PAT-pc	PAT-ps
Assembly	PAT-asc	PAT-ac	PAT-as
Testing	PAT-tsc	PAT-tc	PAT-ts

Figure 6.8. PAT processes occur in all procedures and at all levels.

Fabrication Processes, Packaging, Assembly and Testing

Fabrication processes, specifically intended for electronic chips and microsystems, are discussed in other chapters of this report. The range of processes available for micromechanical parts generation and joining is expanding rapidly since processes are the facilitators of progress in the MEMS area. New processes, as they develop, will also be used in PAT. Table 6.1 briefly reviews processes that have already been used in MEMS devices.

Packaging systems can be classified according to levels of sealing enclosure. Table 6.2 reviews levels in terms of open or closed -- rigid, flexible, sealed or exposed.

Table 6.2
Packaging Levels

CLOSED - Rigid or with Flexure

- Closed - Rigid
  - Acceleration, Temperature, Light, Vibration, EM Fields
- Closed - Flexure (for mechanical pass-through)
  - Pressure, Strain, Drag, Tactile

OPEN - Moving Seal or Direct Contact

- Open - Sealed (large motion)
  - Angular Rotation, Linear Displacement, Combinations
- Open - Exposed to External Contact (with materials)
  - Chemical (pH, pO_2, pCO_2, etc.), Electrochemical

Assembly processes occur at subsystem, component, and complete system levels. Approaches can range from integrated techniques such as silicon micromachining to automated assembly to classical manual assembly. Many examples of integrated methods are contained in the other chapters of this report. Assembly procedures, manual or automated, include steps such as parts acquisition, transfer, insertion, placement, and connection. Most real examples of assembly are system-specific, with the greatest success in environments that require uniaxial placement of elements on planar substructures. Systems requiring three-dimensional placement and attachment are more difficult.

Testing for electrical properties in microsystems is a well developed art. Testing the mechanical properties of MEMS-based devices is not. Whether examining movements, surfaces or materials properties, the testing of micromechanical devices presents serious barriers. Objects are difficult to observe in operation. Depth-of-field restrictions in optical systems limit the observation of highly three-dimensional systems. Nonoptical viewing systems necessarily require environments that might prevent operation of the targeted microsystem. Small systems cannot be touched safely or interconnected without altering function or causing system damage. Signals produced are very low so measurements, again, can alter system function.

SAMPLE PACKAGES -- LEVELS AND PROCESSES

Issues in PAT are clearly diverse, and their inclusion in the system design can add substantial complexity to the product development process. Conversely, the exclusion of PAT issues in the development process can render an otherwise good R&D project useless. The definitions in Table 6.3 summarize the diversity of issues that should be considered in the following sections.

The following examples provide a quick overview of a series of progressively more complicated examples of fabrication, packaging (open or closed), and assembly (integrated or manual).

Table 6.3
Summary of Diversity of Issues

Elements	chips, connectors, boards, wires, fixtures, etc., within a package
Manufacturing Procedures	fabrication, assembly, test
Product Level	subcomponents, components, complete systems
Packaging Levels	closed-rigid, closed-flexure, open-sealed, open-exposed
Assembly Procedures	acquisition, transfer, insertion, placement, and connection
Package Definition Measures	geometry, protection, interconnection
Testing Approach	direct contact, noncontact, inferential
Tested Properties	geometry, material properties, parts interaction, overall functions
Testing Stages	performance, product clearance prior-to-sale, continuing operation
Yield	product percentage emerging after manufacture

Example 1: Closed-Rigid Subsystem Level

Figure 6.9 shows a micromachined accelerometer developed by Analog Devices Corporation. The system includes microelectronics, micromechanical flexure-supported masses, sensors, and actuators for self-testing the sensor prior to each use. The microsensor is assembled via integrated techniques, and then packaged in a closed-rigid package. An integrated approach for packaging such systems is also shown in Figure 6.10.

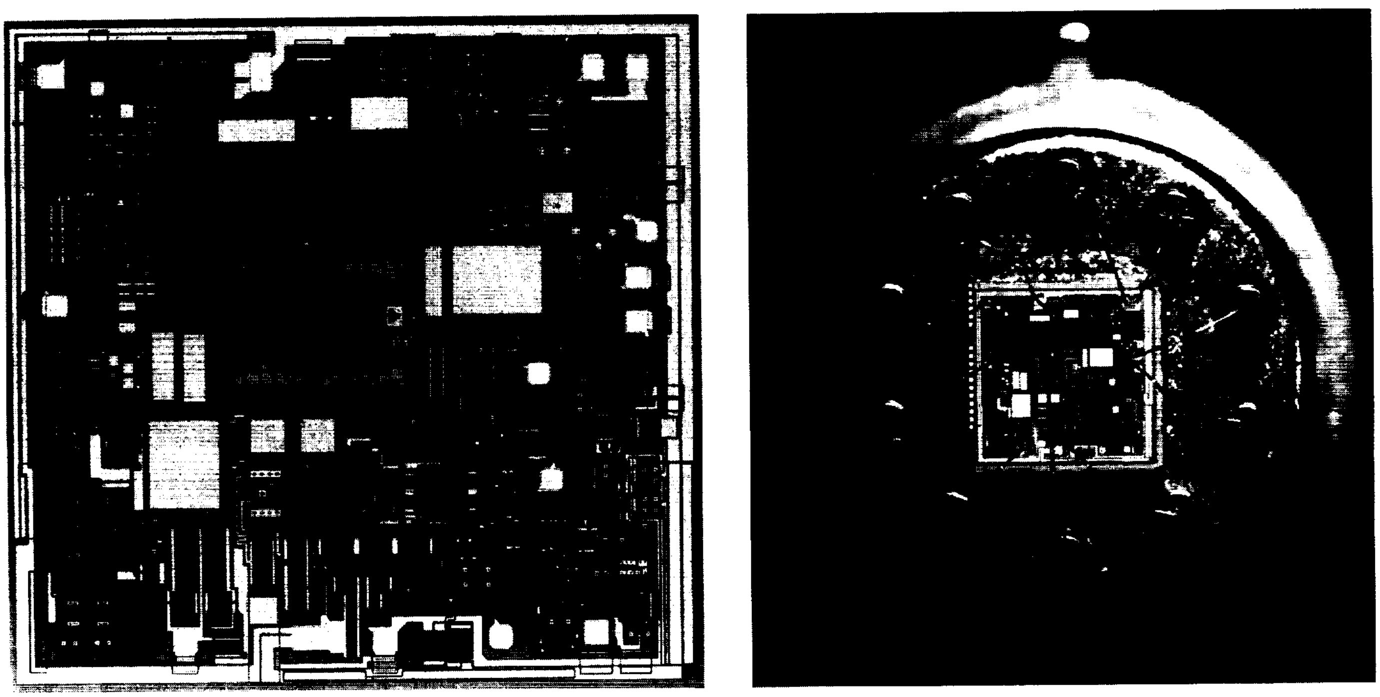


Figure 6.9. Integrated accelerometer - Analog Devices (USA).

Example 2: Closed-Flexible Subsystem Level

Figure 6.10 shows an integrated pressure sensor developed by NOVA Corporation. The sensor includes a flexing diaphragm, with deflection sensed by strain sensors integrated into the chip. Pressure must act directly on the chip or be isolated by a package that itself includes a sealed, flexible member. Assembly techniques involve very sensitive manual techniques with demands on placement and electrical connection. Equivalent systems are produced in Japan, Europe, and the United States using similar approaches.

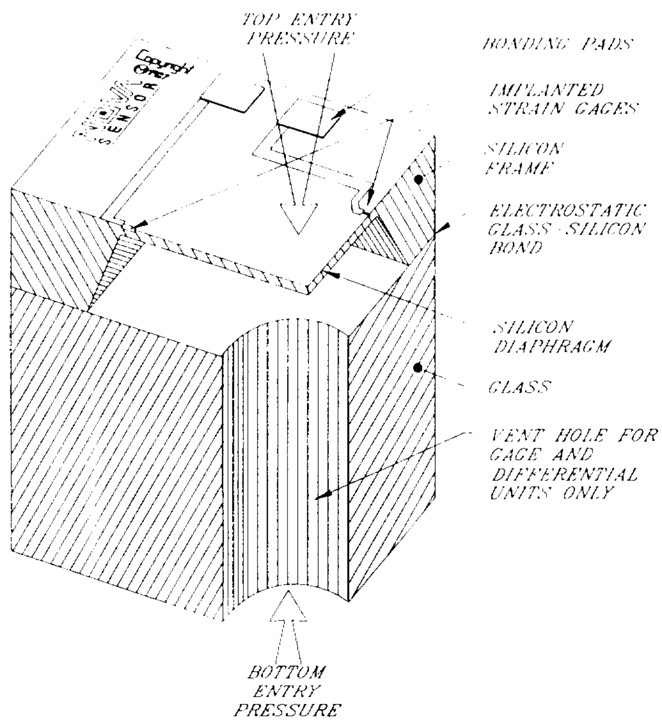
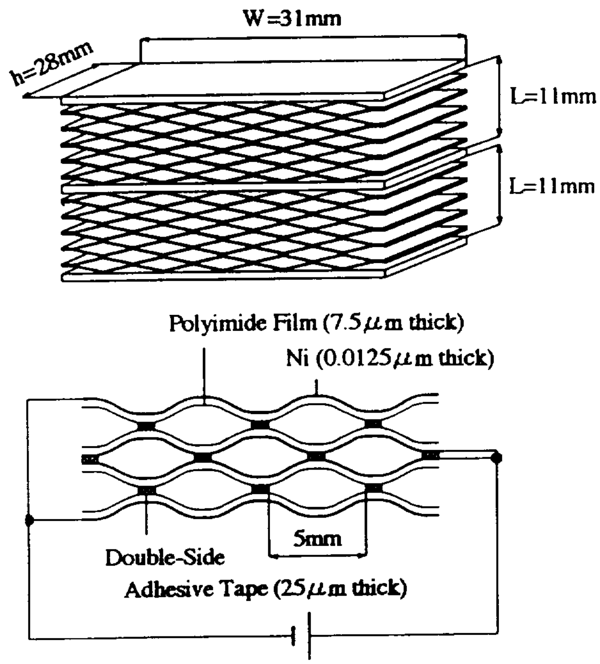


Figure 6.10. Integrated pressure sensor - NOVA (USA).

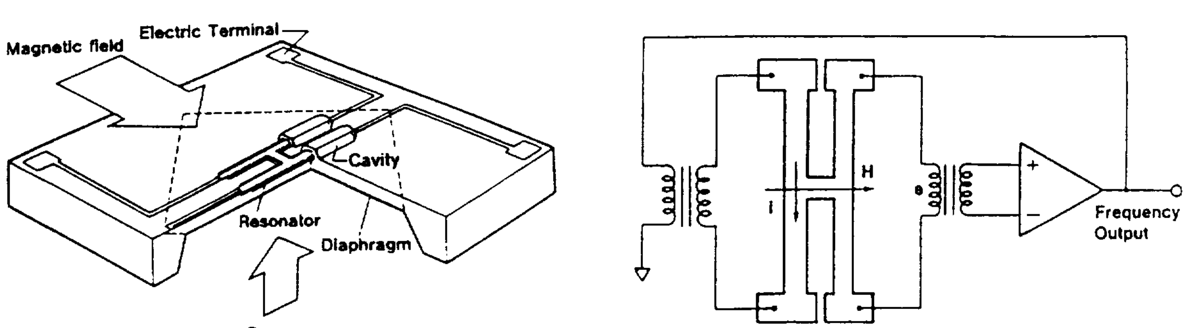
Figure 6.11 shows a novel approach to the development of electrostatic microactuation being developed at Tohoku University (Japan). The system uses deforming films in series-parallel combinations in order to achieve desired strength-displacement characteristics. PAT methods for rigidly enclosed systems (for example, optical or null-sensor applications) are available. However, flexible seals for small actuation deflections must be developed that permit low force movement, easy assembly, and low cost. Methods for large excursions, with seals, are nonexistent and will involve significant difficulty in development and manufacture.

Figure 6.12 shows a very interesting integrated micropackage for a micromachined resonant element used to detect the deflection of a pressure-measuring diaphragm. The system, developed by Yokogawa (Japan), involves the formation of a beam-type oscillator driven at resonance by integrated surface actuators. The beam system is then sealed in on the pressure diaphragm, and shifts in resonance indicate diaphragm strain. The package is ideal in that important parts are totally isolated and output is easily converted to digital form. Assembly and testing procedures are similar to the system shown in Figure 6.10.



Schematic diagram of the macro model of the pair actuators which attract alternately each other. Main structure was fabricated with polyimide film. Two DEMAs are connected in series.

Figure 6.11. Deforming film actuators - Tohoku University (Japan).



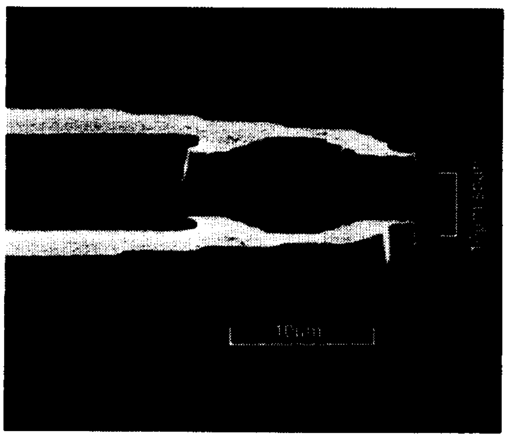
Construction of Micromachined Resonant Pressure Sensor

Schematic Diagram of Oscillation System

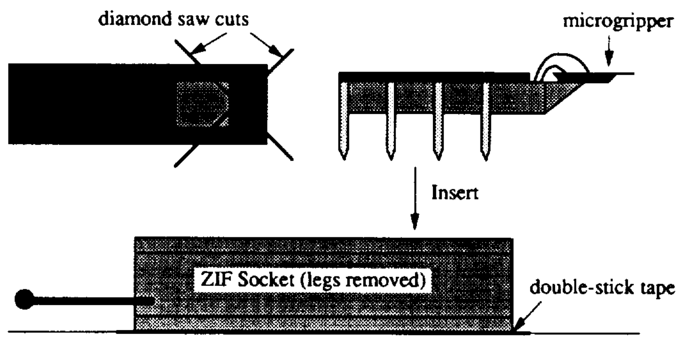
Figure 6.12. Micromachined resonant pressure sensor - Yokogawa (Japan).

Example 3: Open-Sealed Component Level

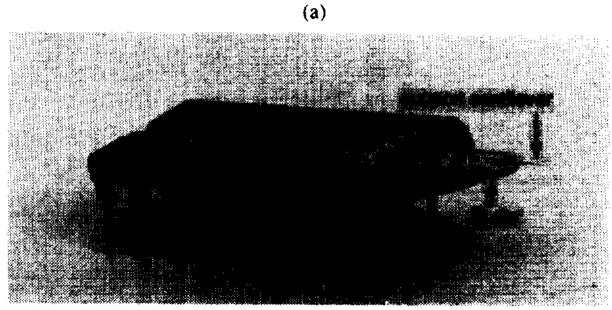
Figure 6.13 shows a set of microforceps developed at UC Berkeley (United States). The forceps is a system of components that includes a base for mounting and electrical interconnection. The forceps, an integrated extension of a base chip, are actuated electrostatically. The system, which is intended to be a demonstration of concept, will now require a not insignificant focus on procedures for packaging and assembly. In short, the value of such a system and the beauty of the concept are unquestionable -- its practical realization will require additional work and perhaps a totally different fundamental approach due to PAT issues.



Close-up SEM micrograph of microgripper jaws.

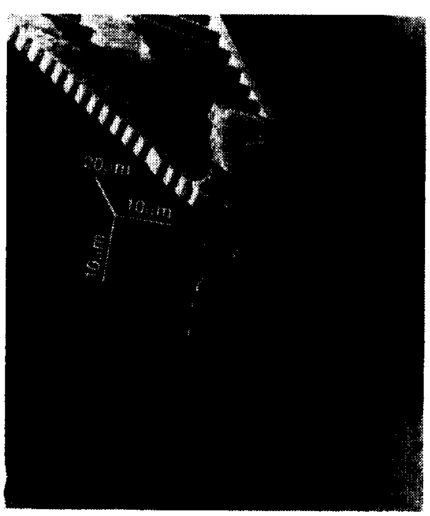


(a)



(b)

(a) Schematic showing gripper packaging and electrical access.
(b) Photograph of the packaged gripper.



SEM picture of a one-celled protozoa, a euglena, being held by the microgripper. The euglena is 40 μm long and 7 μm in diameter.

Figure 6.13. Microforceps - Berkeley Sensor and Actuator Center (USA).

Figure 6.14 shows the internal and package elements for a rotary displacement transducer (RDT) being developed at the University of Utah (United States). The RDT is physically assembled at open-sealed component level. The housing, with seals and bearings, contains a base chip that contains rotation-sensing arrays of detectors. The shaft holds a circular array of emitter features that drive the detectors. Assembly procedures are direct and require substantial attention to shaft runout and alignment. The package is sealed, but not hermetically, due to the rotary motion required between the input shaft and the sensor housing. Testing procedures involve conventional access methods to the chip, but are unique and difficult (high rotational precision) when evaluating total system performance.

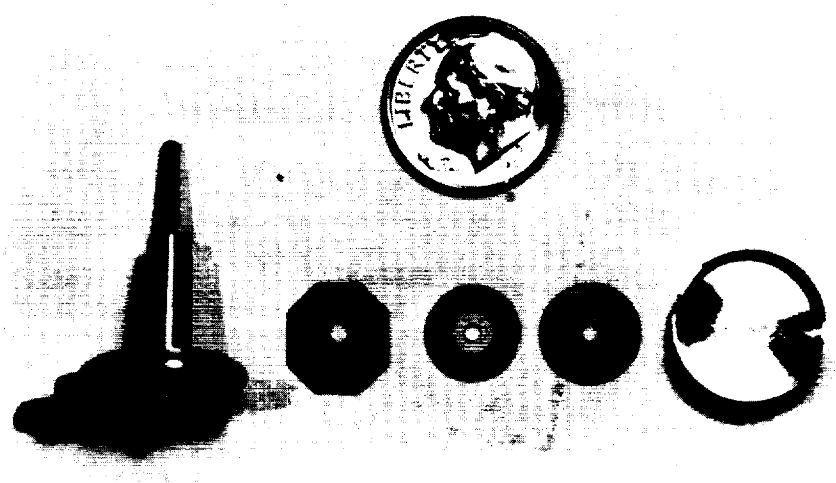


Figure 6.14. Rotary displacement transducer (RDT) - University of Utah (USA).

Figure 6.15 shows the emitter-detector chips for the RDT. The base chip includes arrays (grey-code and vernier) of capacitive detectors and associated circuitry for sensor management and multiplexing information onto a digital bus in coordination with 127 other sensors. The base chip is CMOS with after-processing etching, to produce different planar levels and surface treatments appropriate to form long-life bearings. The base chip interacts with emitter elements on a close-proximity sapphire disk, which is suspended over the base chip by a central rotor shaft, and the integrated bearings on the chip and disk surfaces.

Figure 6.16 shows an electromagnetically driven microvalve being developed at NTT (Japan). The system includes a base over which a magnetizable valving element is suspended by silicon micromachined flexures. Magnetic field interactions actuate the valving element, which modulates a 30-micron orifice. The field is produced externally (sealed), but internal components are exposed to the flow field (open). Packaging requires new types of structures, and assembly procedures are mixed in that they involve both integrated and manual steps. With low gas flows and high band width (up to 100 Hz), testing also requires unique approaches for flow measurement. Fouling, liquid effects, corrosion, particulate intrusion, and other problems will all present unique PAT and use problems for the system.

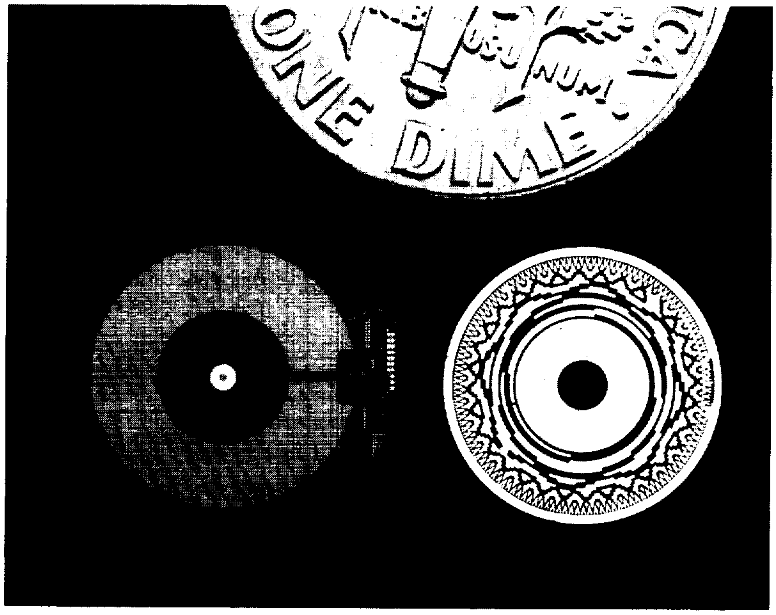


Figure 6.15. RDT emittor-detector chips - University of Utah (USA).

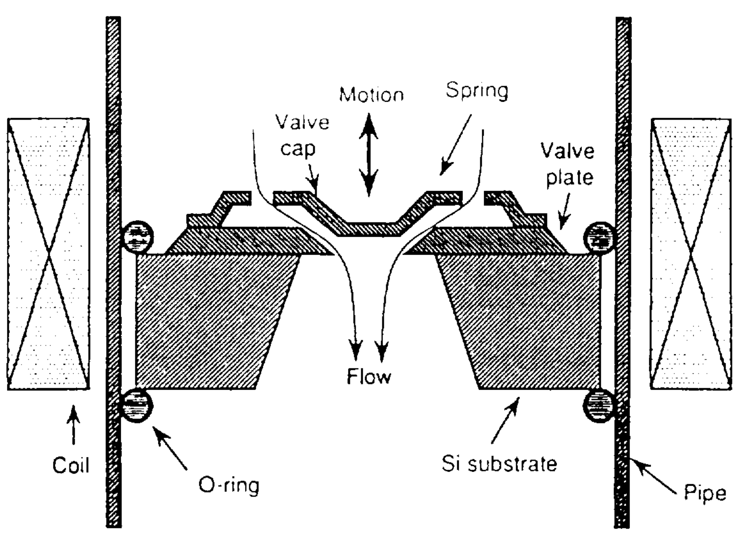


Figure 6.16. Electromagnetically-driven microvalve - NTT (Japan).

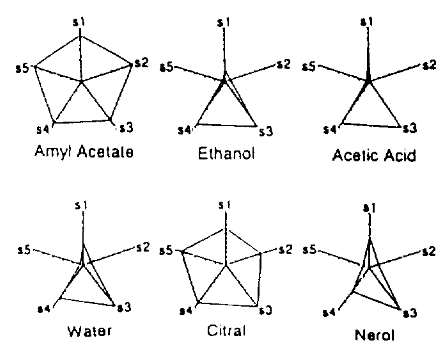
Example 4: Open-Exposed Component Level

Figure 6.17 shows a very interesting odor sensor being developed by Yokogawa (Japan). The sensor uses a quartz crystal microbalance, driven at resonance, to detect the presence of odorants such as amyl acetate, ethanol, acetic acid, and others. Fabrication includes the semi-integrated assembly of the crystal resonator and a PVC-blended lipid membrane. During use, the membrane is exposed to the medium to be sensed, so that selective uptake-outgo processes cause mass variations that alter the resonance frequency of the system. The packaging approach will be unique, since it requires the isolation of electronically active elements and open exposure to fluids to be sensed. Testing requires conventional chemistry and the pattern-like recognition of the output of five sensor elements. Details of the PVC sensing element were not disclosed.

○ Methods for Odor Measurement

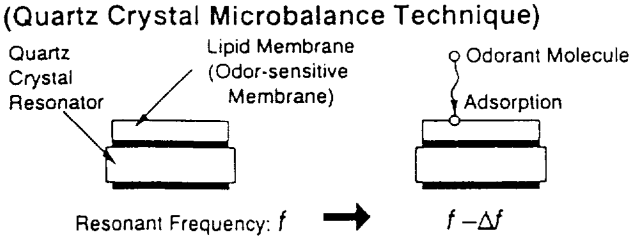
Method	GC/MS	Semiconductor	Quartz Crystal Microbalance	Membrane Potential
Advantages	• Precise Analysis	• Stability • Long Life	• Human-like Selectivity	• Same Principle as Human Olfactories
Disadvantages	• Large-scaled • Correspondence with the Human Sense • Off-line Measurement	• Correspondence with the Human Sense	• Poor Sensitivity and Response (Conventional Ones)	• Future Technology
Principle etc.	Instrumental Analysis	Conductance	Resonant Frequency	Electric Potential

○ Recognition of Odorants



Output Patterns of Five Sensors for Various Odorants

○ Structure and Principle
(Quartz Crystal Microbalance Technique)



• Detect the mass change of the lipid membrane induced by the adsorption of odorants by measuring the resonant frequency shift of a resonator

• Δf [Hz] = $0.083 \cdot \Delta m$

Δm : Mass Change (ng/cm^2)
(6MHz At-cut Resonator)

Figure 6.17. Odor sensor - Yokogawa (Japan).

Figure 6.18 shows another interesting concept for an integrated sensor system that falls in the open-exposed category (under development at the University of Michigan). The system proposes the use of heaters (actuators), temperature sensors, pressure sensors, and thin film gas sensors, all integrated onto a single chip. Due to its integration, packaging and assembly of the system will be straightforward. Its successful, chronic, and direct exposure to fluids-being-sensed will present problems.

Figure 6.19 shows a microciliary motion system being developed at the University of Tokyo (Japan). The system is composed of a large array of individual, thermally actuated microbeams that can act in groups to produce mechanical effects at the surface of the array. Assembly of the system at the chip level is integrated, but if multiple systems are to be used, manual techniques are required. Packaging represents substantial problems if protection of the apparently fragile elements is to be achieved. Testing procedures so far involve optical examination of individual beam performance and the ability of the coordinated arrays to interact with objects in direct contact.

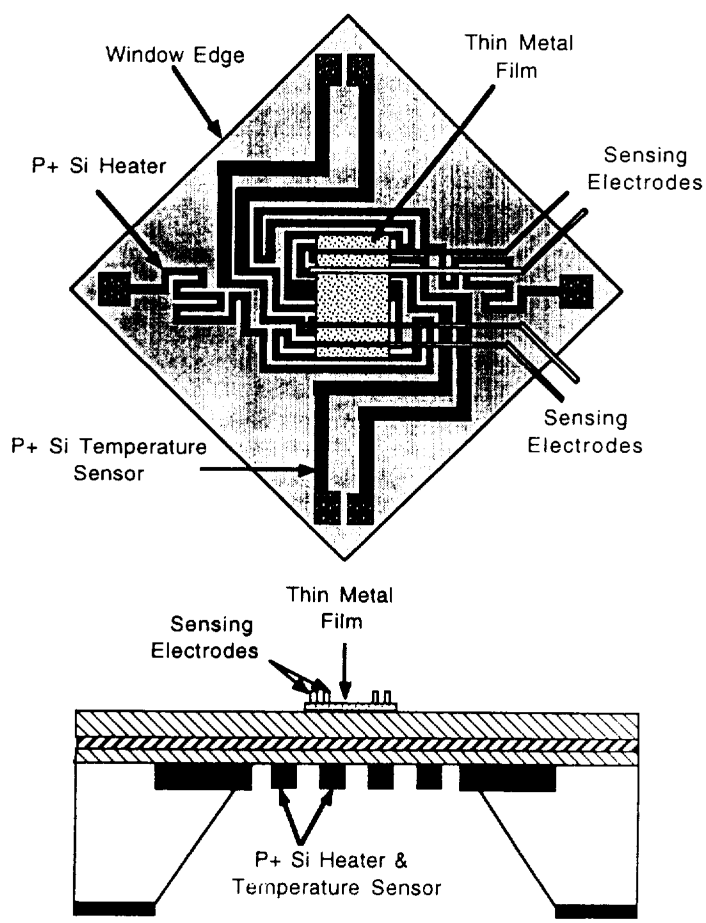


Figure 6.18. Silicon micromachined gas detector - University of Michigan (USA).

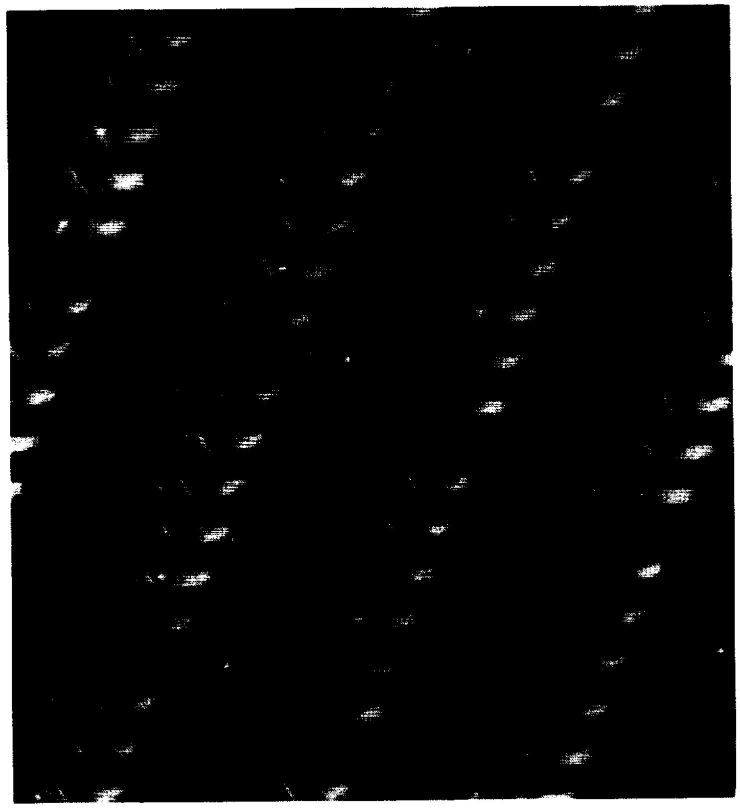


Figure 6.19. Microciliary motion system - University of Tokyo (Japan).

SUMMARY AND CONCLUSIONS

General - Review of Observations

Organizations visited are listed in Table 6.4 (with no particular ranking). Examples of projects and products observed during the visit are reviewed in Table 6.5. Examples of processes, materials, and packaging projects observed at various organizations are reviewed in Table 6.6. Many of the figures in the previous section represent work from Japanese organizations.

Information Availability

The Japanese routinely achieve high levels of competence in all areas of PAT. Their appreciation for detail and emphasis on quality is evident in this respect. Japanese efforts in PAT can be subdivided into three categories: (1) R&D projects; (2) current product development; and (3) products currently sold in the marketplace. Three types of organizations were visited by the team: (a) universities and industrial research laboratories; (b) government organizations; and (c) commercial operations in corporations. Information in each category was available or unavailable to the JTEC team from each organization depending on its relationship with commercial competitive issues. Category 1 information had mostly longer-term impact and was discussed openly by all organizations (a, b, and c). Category 2 information was only known by commercial corporations (c). Because the corporations were sensitive to the competition, and because the product development process was short-term and confidential, Category 2 information was not discussed. Category 3 information was available everywhere. For example, an examination of products on sale (watches, automobiles, electronics, etc.) in downtown Tokyo revealed the outstanding capability of the Japanese to efficiently execute PAT processes.

Table 6.4
Organizations Visited by Group

SITES VISITED BY CHAPTER AUTHOR	SITES NOT VISITED BY CHAPTER AUTHOR
MITI	Mitsubishi Electric
Micromachine Center	Hitachi
NTT	Matsushita
University of Tokyo (1) Ind. Sci., (2) Mech. Info., & (3) Eng. Prod.	Nippondenso
Canon	Nagoya University
Olympus	Seiko Instruments
Tohoku University & Tohoku Gakuin University	Kanagawa - Sci. & Tech.
Yaskawa Electric Corp.	Toyota
Omron	SORTEC Corp.
Yokogawa Research Lab.	

Table 6.5
Projects and Products Observed

Laser Guided Magnetic	Suspension Sys. Small Motors - Many Kinds
Micromagnetic Suspension	Optically-Based Catheter Tip Pressure Sensor
Multiple Degree-of-Freedom ATM	Interleaved Transverse Electrostatic Actuator
Fluidic Actuator	Zero Temperature Coefficient Piezoresistor
Thermal Bimorph Actuator	Silicon Dioxide Disk on End of Optical Fiber
Meisner Levitation System	Commercial pH and pCO2 Sensors - ISFETs
Microair-Hole Levitation	Resonant Systems for Accel. & Gyros
Comb Drive Systems - Tweezers, Valves,	S.M.A. Actuated, 10 mm Diameter Catheter
Motor	Highly Sensitive Resonant Infrared Sensor
On-Chip Tunneling Device	Integrated Capacitive Accelerometer
On-Chip Scanning Force Microscope Probe	Integrated Capacitive Pressure Sensor
Sensor Module for Vision or Display	Silicon Etched Waveguide
High-Speed A to D Converters	Miniature Optoelectric Transformer
High-Speed Photo Systems	Field Emission Magnetic Field Sensor
Mother Ship Project Antennas	Microheaters
High Sensitivity Odor Sensor	Infrared Sensor using Micro-Air-Bridges
Electromagnetic Microrelays	Flow Sensor - Anemometer Based
Microoptical Encoder	Vacuum Sensor
Integrated Optical Disk Reader	Humidity Sensor
Electrostatic Fiber Optic Aligner	Control of Teleoperated Robots
Camera at the Tip of a 10 mm Endoscope	Force Balanced Accelerometer

Table 6.6
Processes, Materials, and Packaging Observed

Advanced Materials and Super Lattices	Piezoelectric Actuation Systems
Langmuir Blodgett Films	Silicon to Silicon Fusion Bonding
Photo-Induced Preferential Anodization	Nonsticking Micromachined Parts
Packaging of Resonant Sensors	Anodic Bonding
Hybrid and Monolithic Chip Mounting	X-Ray Exposure Stepper
Three-Dimensional Microfab.	Micro-EDM, Welding, & Drilling
Super Fine Particles Fabrication	Glass-Silicon Anodic Bonding
Super Conductivity	High Aspect Ratio Parts Fabrication
Bioremediation & Recycling Systems	Focused Ion Beam Techniques
Optical Systems	Terra-Hz Frequency Devices ISITs
Multimedia Optoelectronics with LANs	Various Deposition Systems
Nanometer Scale Systems with Efforts on:	Scaling Effects - Elect. & Mag. Motors
Small Hole Surface Meas. with	Bacterium Flagella-Based Locomotion
Vib. Microprobes	Gallium Arsenide Fabrication
Solar Cells	Photo and E-beam Lithography
Microfluidics for Sensor and Fluid Processing	Ciliary Motion Systems
High-Speed Directional Low-Temp Dry Etching	Micromachining for Packaging of SASs

It must be mentioned here that information control practices observed by the panel in Japan were identical to those found in the United States and Europe. Most commercial organizations, regardless of where they are located, will not make hard-earned information in all categories available to visitors.

General Observations on Japan and PAT

Attitude. The Japanese hosts were cordial and friendly to the JTEC group. Hosts were open and were willing to discuss projects, plans, and products within the limits of good business practice -- which meant that longer-term issues were reviewed openly, whereas strategic planning, current product intentions, and business practices remained confidential.

Approach. The Japanese appear to achieve success the same way all organizations do -- with a lot of hard work, efficient educational processes, a little magic, and much trial and error.

It was clear that our hosts tended to consider entire problems rather than pursue the type of uncoordinated, hobby-like, developmental projects found in many other places. They plan their work very carefully and understand the efforts-chain for their area of effort (Chain = Technology → Project → Component → Product → Market → Business). In some cases, where the size of the commercial opportunity justifies investment, organizations are willing to wait five years before reviewing a project and ten years before expecting a final result. Many times, as a project nears commercial implementation, it is submerged into a corporation where it is made into a final product.

The Japanese attempt to understand technical barriers and plan around them. For example, the development of processes, which they consider to be important in the future, is supported in advance and on a long-term basis. For example: (1) the super clean room effort is well supported and focuses on the development of very high speed microcircuits; (2) the Japanese have expensive facilities necessary for advanced processes such as LIGA; and (3) groups at both Matsushita and Tohoku University are involved in the development of three-dimensional microfabrication processes.

The Japanese attempt to define solid targets. Necessary performance requirements for a system are well defined so that efforts can be logically expended toward a goal, rather than proceeding endlessly toward moving targets. In addition to longer-term projects, the Japanese are keenly aware of the importance of today's dollar. Developments, as they move toward practicality, are planned to occur in successive commercial product cycles -- each having product value and serving as a basis for the next generation of products.

Development Strategy. Central organizations such as MITI attempt to create broad focus by encouraging R&D staff to target commercial products. They believe that coordinated component development leads to better integration, and use national projects as inducements for development groups to work comprehensively together. For example, the powerplant maintenance applications thrust of the MITI micromachine program includes many cross-disciplinary projects, such as the microcapsule, mother ship, wireless inspection module, wired operation module and associated focus on energy supplies, actuator mechanisms, sensors, communication systems, controllers, and other elements. Although some may have reservations about their approach, it has worked in the past and is clearly better than having no strategic plan at all.

The Japanese seem to view MEMS as an important area in that it can function as discriminating technology, which can provide leverage for sales of commercial products. Many hosts indicated that, in the MEMS area, silicon-related fabrication processes were important but that other, less standard techniques were being developed by their groups. They also expressed substantial interest in minisystems, which are larger than microsystems, and indicated that, in the nearer term, minisystems can have a great competitive impact.

Efforts in the PAT Area. The Japanese are very good at developments in the PAT area. Their work, as demonstrated by their commercial product successes, is ahead of that of the United States, even though much current work was not discussed. Across-the-board, Japanese products reveal considerable expertise in sometimes-considered-mundane areas such as seals, enclosures, valves, modularity strategies, assembly processes, testing for quality, cosmetics, and so forth. Certain hosts indicated that packaging and assembly processes will dominate the economics of final products, as well as substantially determining factors related to product ruggedness, reliability, and maintenance. They indicated that PAT approaches must become broad based, and developed along with fabrication processes.

CHAPTER 7

MEMS DESIGN TECHNIQUES, APPLICATIONS, AND INFRASTRUCTURE

Joseph M. Giachino

INTRODUCTION

Japanese researchers have no universal definition of MEMS. Some groups think of MEMS as microelectromechanical systems manufactured by integrated circuit processing, mainly in silicon. Other groups think of MEMS as systems that are manufactured by any means as long as microscaled elements are included as part of the system. These systems would most likely not be made of silicon. Japanese universities and industrial research facilities are doing much more extensive work than the United States in nonsilicon MEMS via traditional machining.

In the United States, MEMS has been used to embrace microminiature systems that are constructed with both IC-based fabrication techniques and other mechanical approaches. In most cases, an emphasis has been placed on having the techniques compatible with IC techniques to insure the availability of electronics close by. Most researchers require that MEMS be contained within the same package, while some require that MEMS be contained on a single chip.

To date, the integrated circuit industry has been the technology base that has driven MEMS. This is shown in both the bulk silicon and polysilicon efforts that have been the mainstay of MEMS devices. The MEMS community has made significant advances in the area of deep etching bulk silicon and in surface (sacrificial etching) micromachining with polysilicon. MEMS has driven the silicon community into understanding the mechanical properties of silicon structures in addition to the electrical properties. MEMS has also been a driver behind research into alternative, non-IC-based techniques to obtain microdevices. These techniques include LIGA, laser-assisted CVD, electroplating, electroless plating, and, especially in Japan, conventional machining.

DESIGN TECHNIQUES

The design techniques used for MEMS in Japan are basically the same as those used in North America. The mechanical designers use finite element modeling (FEM) and 3-D computer-aided design to determine the original design. After testing, the models are adjusted based on the empirical data obtained. While not explicitly stated, it is apparent that analytical models are also used and corrected as test data become available.

Electrical IC modeling is used for silicon integrated MEMS devices. This is especially true of the commercial sensors that are under development where circuit simulation originally developed for LSI is applied to MEMS.

There is an effort in Japan to obtain electromechanical modeling for MEMS. This would allow a designer to obtain the performance of the total system in the minimum amount of time. Toyota demonstrated an effort to do this at Transducers '93, where the company presented its work in 3-D stress analysis in the crystal lattice to do electrical analysis in three-dimensional anisotropic conductivity (Morikawa 1993). No one has demonstrated an ability to design a MEMS totally in software, as has been done with IC designs, and to do simulations to check performance before actual fabrication. There is general agreement that the development of MEMS would be more rapid if accurate modeling tools were available.

One of the major needs in both Japan and the United States is a good microscale data bank of parameters and material properties. While there are individual efforts in Japan to do this, there is no central agency guiding the effort.

Data are required for both design and reliability modeling. Many Japanese researchers visited by the JTEC team agreed that the lack of good reliability data and a method for predicting lifetimes hinders commercialization of MEMS devices.

There is extensive use of testing and proof of concept-type demonstrations to illustrate the potential applications of MEMS. All researchers interviewed by JTEC agreed that the major requirement for an acceleration of MEMS is commercial success. To date, the technologies used to produce MEMS, especially silicon micromachining, have resulted in some commercial products. However, there are no MEMS devices in commercial use, other than sensors and some microvalves.

APPLICATIONS

The major application of MEMS technology to date is in sensors. These include sensors for medical (blood pressure), automotive (pressure, accelerometer), and industrial (pressure, mass air flow) applications. Commercial sensor applications in Japan are in the same areas that both Europe and North America are concentrating on. In most cases the markets for these products are international.

There are extensive efforts in Japan to apply MEMS to actuators. Dr. Higuchi and his associates at Kanagawa Academy of Science and Technology (KAST) have developed an instrument that is in commercial use to fertilize eggs (1990). The instrument uses a piezoelectric vibrating element to avoid the problem of egg deformation that occurs with conventional methods.

While the commercial applications of actuators have been limited, there is a vast array of actuator needs that MEMS researchers are addressing. These include muscle-like electrostatic actuators, microrobots, noncontacting wafer transport systems, and ultraprecise positioning.

Most researchers estimate that it takes approximately five years to commercialize a product based on a new technology. There are some estimates that it takes two years to do the research prototype, four years to do the engineering prototype, and four years to get the final design to market. There is a large variation in time requirements based on how much process development and trial-and-error development is required, as well as the complexity of the device and how much invention is required.

Many Japanese researchers look on high-aspect-ratio technology (LIGA, polyimide ultraviolet) as new technology for MEMS applications. A substantial number of those visited by JTEC look on the refinement of conventional machining as a new technology for MEMS. This includes conventional milling and EDM. Some researchers consider nanotechnology as a technology potentially competitive with MEMS.

Most Japanese researchers agree that the driving forces for MEMS are size, cost, and intelligence of the sensor. One of the challenges of dealing with MEMS is learning how to effectively package devices that require more than an electrical contact to the outside. Pressure sensors are the most commercially successful MEMS-type sensors to use nonintegrated circuit-type packaging. Hall sensors, magnetoresistive sensors, and silicon accelerometers have used IC-based packaging. The IC packaging is viable since the measurand can be introduced without violating package integrity. Some optical systems use IC-type packages with windows. MEMS will require the development of an extensive capability in packaging to allow the interfacing of sensors to the environment. The very advantage of small size becomes a liability when a device is open to the environment. At the time of the JTEC visits, most Japanese predicted that MEMS sensors would be on the market in three to five years, and that micromedical sensors would probably be the most likely application. Some researchers were predicting that these micromedical sensors would be chemical sensors.

U.S. researchers forecast that in the near future (ten years), MEMS systems will have applications in a variety of areas, including:

- o Remote environmental monitoring and control. This can range from sampling, analyzing, and reporting to doing on-site control. The applications could range from building environmental control to dispensing nutrients to plants.

- o Dispensing known amounts of materials in difficult-to-reach places on an as-needed basis. This could be applicable in robotic systems.

- o Automotive applications will include intelligent vehicle highway systems and navigation applications.

The Japanese forecast for MEMS actuators was not at all clear at the time of the JTEC visit. There was much interest expressed in exploring arrays of actuators as a method of obtaining useful work. Some researchers expressed interest in pursuing low mass applications such as directing light beams, based on the success of the Texas Instruments optical array (Sampsell 1993).

One of the major concerns with some true MEMS systems (those on the micron level) is that they must at some point be coupled to a macroworld. Some researchers see an application for a "milli" system, where the problems of coupling to the macroworld are made easier. If one can have a useful product that is all on the microlevel with only an electrical output, then the concern is eliminated.

A broad overview of the potential applications of MEMS is seen in MITI'S "Techno-Tree of Micromachine" (Figure 7.1).

In its Micromachine Technology Project, MITI has targeted two major application areas for MEMS -- maintenance of power plants and medical applications. The advance maintenance system for power plants (see Figure 6.5, p. 84) consists of:

- o Mother ship (Figure 7.2)
- o Microcapsule (Figure 7.3)
- o Inspection module (Figure 7.4)
- o Operation module (Figure 7.5)

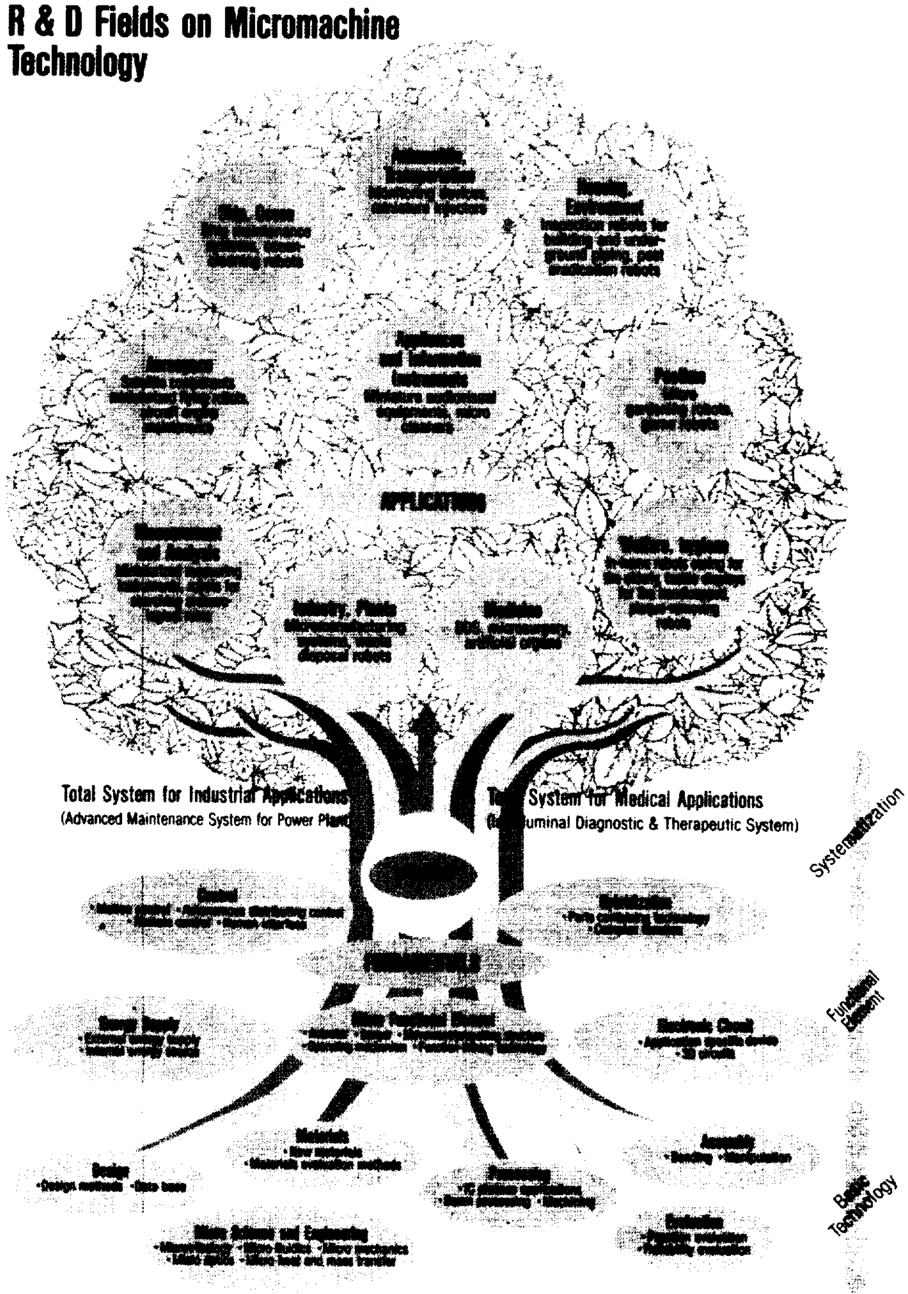


Figure 7.1. MITI "Techno-Tree of Micromachine."

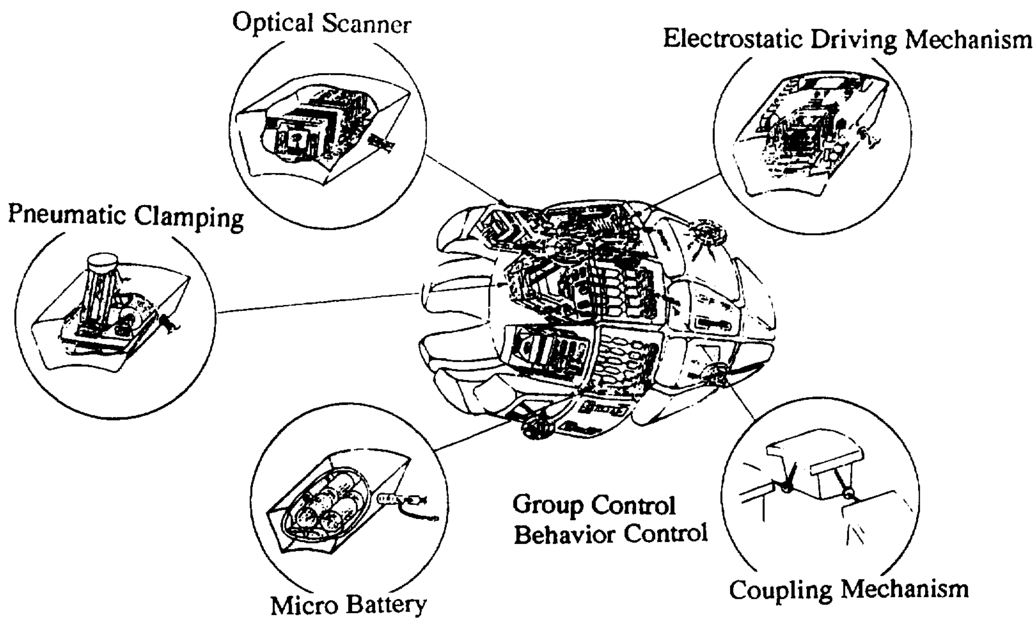


Figure 7.2. Mother ship.

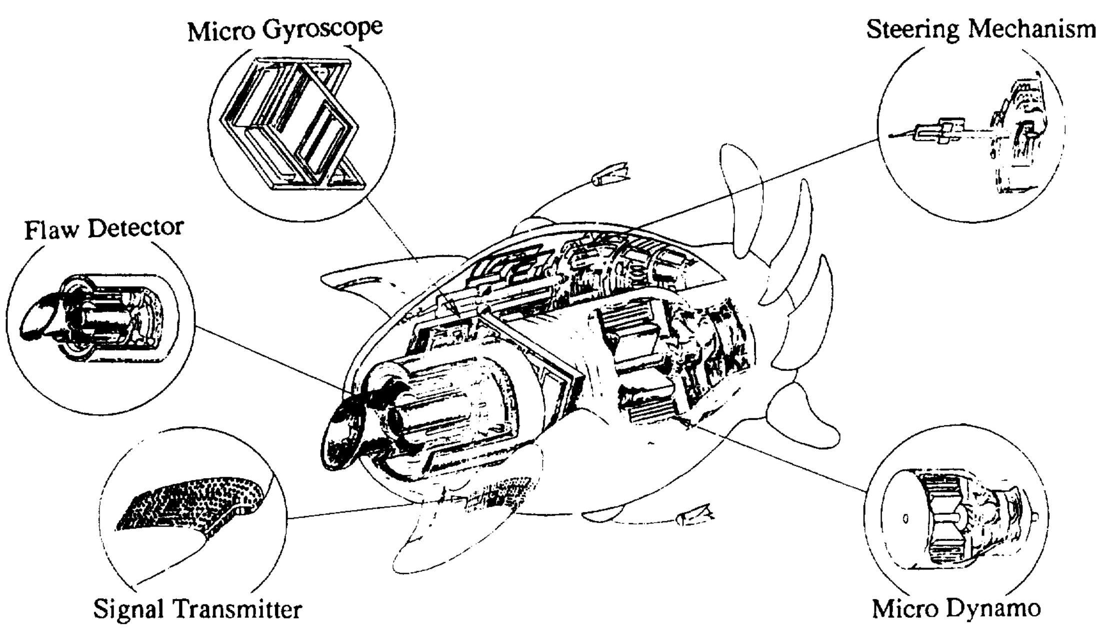


Figure 7.3. Microcapsule.

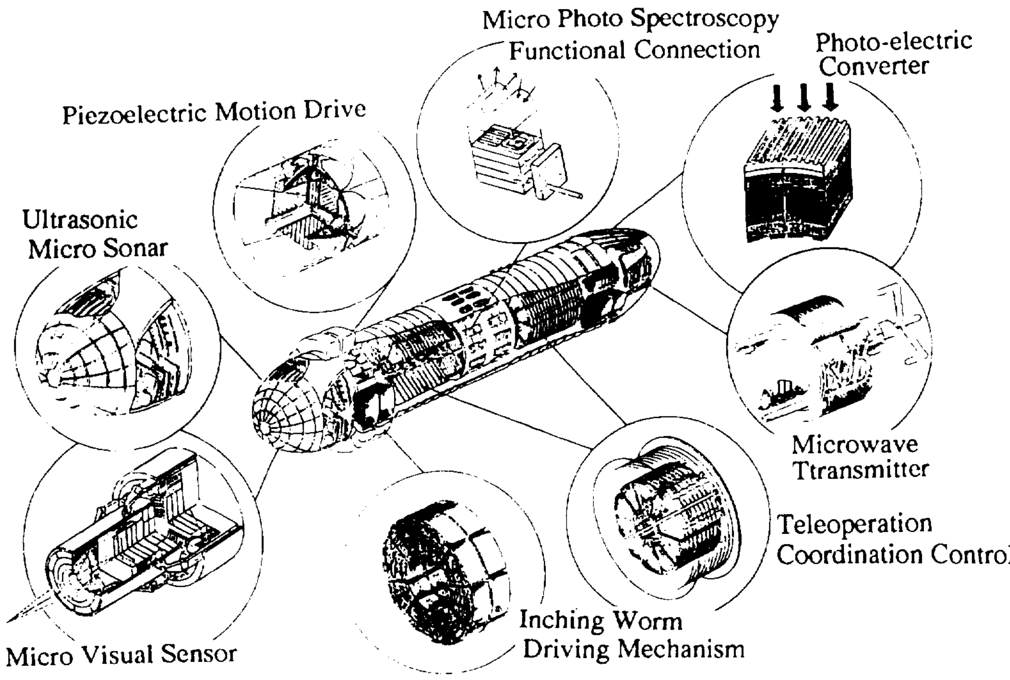


Figure 7.4. Inspection module.

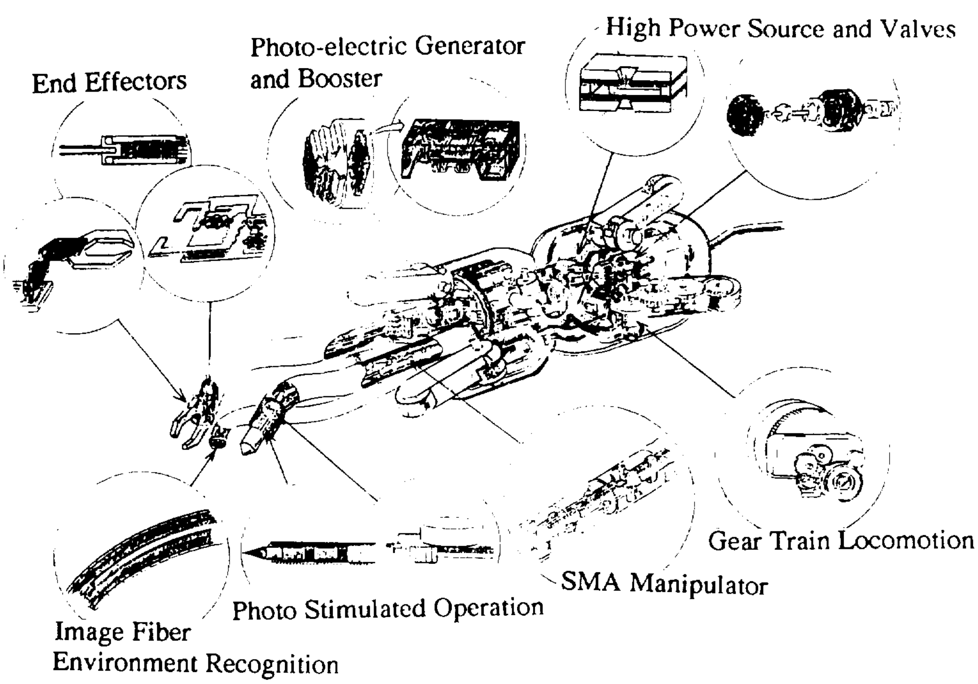


Figure 7.5. Work module.

The purpose of this elaborate system is to do repairs in heat exchanger tubes with no or minimum down time. It should be noted that even if only a portion of this task is completed, a large number of the resulting MEMS components could be utilized in other industrial applications.

Another MITI-targeted area is medical use of a microcatheter for cerebral blood vessel procedures. The inner and outer duct of the potential microcatheter are shown in Figure 7.6 and Figure 7.7.

A potential third application under investigation by MITI is targeted at energy savings in manufacturing. The development of microrobots could aid in the manufacturing and assembly of semiconductor devices in clean rooms much smaller than those now in use.

It is obvious that the MITI-proposed applications are both broad in scope of application and in their social impact.

Other Japanese researchers also are investigating making small factories to build small MEMS machines.

INFRASTRUCTURE

The infrastructure that is used to support and direct MEMS in Japan is different from that in the United States. The most striking is the ten-year commitment by MITI to a very ambitious program to develop enabling technologies. A further goal is to establish a commercial base for the production of MEMS.

While target funding for the total program is ¥25 billion, only ¥2.43 billion have been actually allocated to the program in its first three years. The funding is directly linked to tax revenues. It was noted that Japanese companies participating in the MITI program have substantial internally-funded R&D activities in this area. AIST estimated that of the 270 researchers working on micromachines in 23 participating companies, 80 are funded by their respective companies. One company estimated its expenditures to be in the neighborhood of ¥200-300 million per year.

The structure of the MITI program is shown in Figure 7.8. As indicated in the figure, Three national laboratories are funded directly by AIST under this program: the Electro-Technology Laboratory (ETL), the Mechanical Engineering Laboratory (MEL), and the National Research Laboratory of Metrology (NRLM).

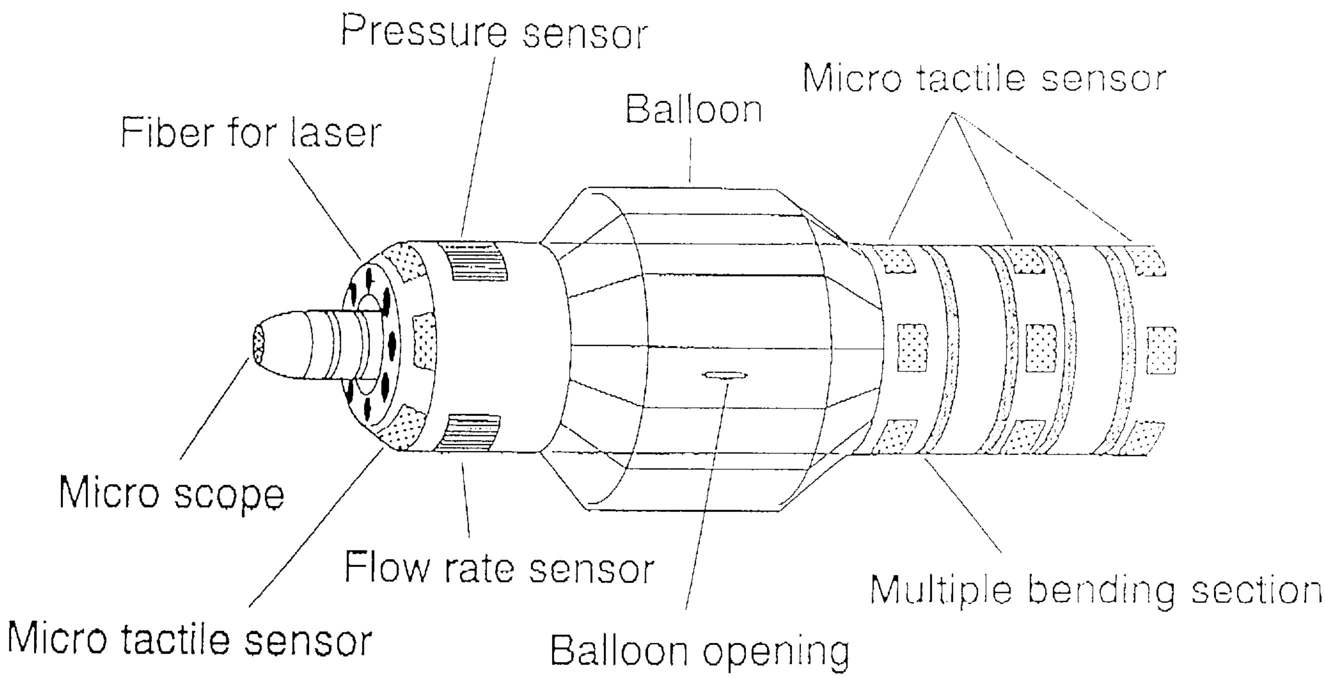


Figure 7.6. Outer duct of the potential microcatheter.

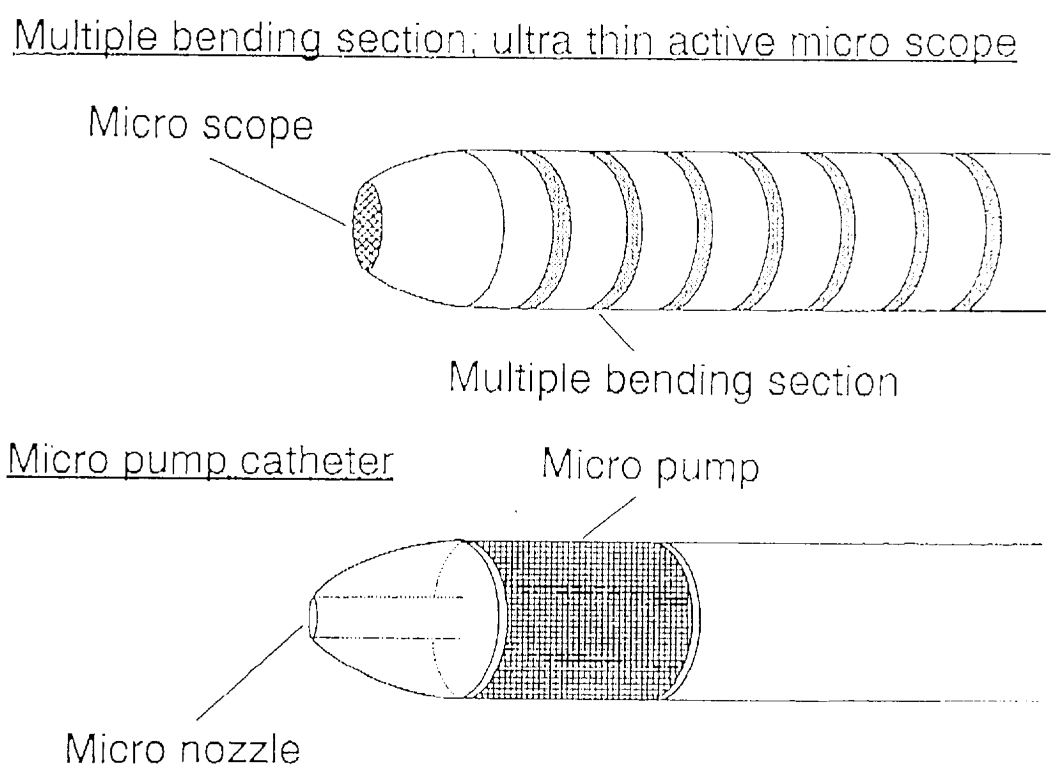


Figure 7.7. Inner duct of the potential microcatheter.

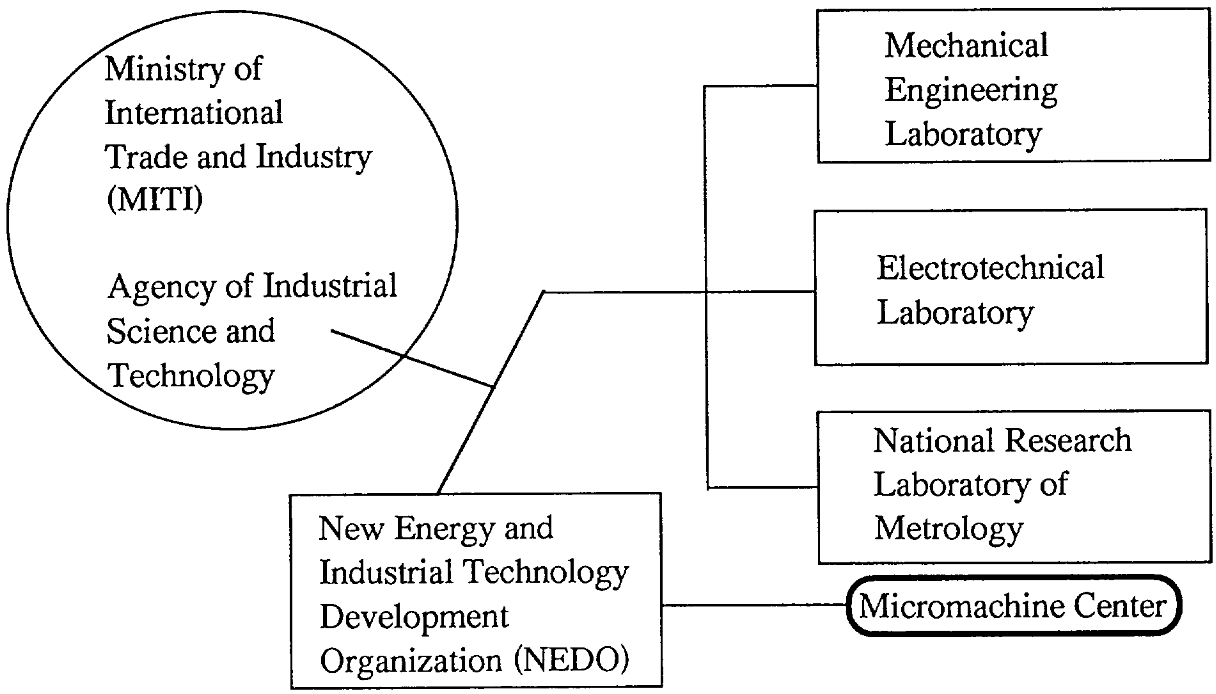


Figure 7.8. Structure of the MITI program.

Industrial participation in the program is managed through the New Energy and Industrial Technology Development Organization (NEDO) under AIST. NEDO in turn contracts with the Micromachine Center (MMC) for management of the individual research projects. Each member of MMC pays a membership fee that is used to pay MMC's overhead and to fund the non-Japanese companies.

There are four types of membership: "Research Supporting," "Group Supporting," "General Supporting," and "Special Supporting." Current membership in each of these categories is shown in the MMC site report (Appendix C, p. 159); research supporting membership is shown in Figure 7.9.

The research supporting members consist of those companies that are funded directly by MMC to perform research under the MITI-funded program. Group supporting members consist of two Japanese industrial associations that are interested in the research performed by the center, and the four non-Japanese institutions that perform research for the MITI project. The general supporting members consist of companies that have access to all information developed through the center, but do not have any intellectual property rights in the research results developed with NEDO funds. Membership in this latter category is open, and new members can be added at any time. Membership in the research and group supporting categories is closed, since the terms of membership were determined by

Japan	: 24
U.S.A.	: 2
Australia	: 1

AISIN COSMOS R & D CO., LTD.	Murata Manufacturing Company, Ltd.
FANUC LTD	NIPPONDENSO CO., LTD.
Fuji Electric Corporate Research and Development, Ltd.	OLYMPUS OPTICAL CO., LTD.
FUJIKURA LTD.	OMRON Corporation
Hitachi, Ltd.	SANYO Electric Co., Ltd.
JAPAN POWER ENGINEERING AND INSPECTION CORPORATION	Seiko Instruments Inc.
KAWASAKI HEAVY INDUSTRIES, LTD.	SUMITOMO ELECTRIC INDUSTRIES, LTD.
MATSUSHITA RESEARCH INSTITUTE TOKYO, INC	TERUMO Corporation
MEITEC CORPORATION	TOSHIBA CORPORATION
Mitsubishi Cable Industries, Ltd.	YASKAWA ELECTRIC CORPORATION
MITSUBISHI ELECTRIC CORPORATION	Yokogawa Electric Corporation
MITSUBISHI HEAVY INDUSTRIES, LTD.	IS Robotics (U.S.A.)
MITSUBISHI MATERIALS CORPORATION	SRI International (U.S.A.)
	Royal Melbourne Institute of Technology (Australia)

Figure 7.9. Micromachine Center (MMC) - research supporting membership.

MITI, on an individual basis with each company, at the beginning of the project. The fourth type of member, special supporting member, consists of the banking institutions that handle funds for the center. The fees paid by the members become discretionary funds for MMC.

In addition to the national (MITI) project, MMC also administers an independent R&D program using the funds provided by its members. MMC as a private concern is considering supporting university research, which has regulatory constraints for government entities. Most university research is funded through the Ministry of Education.

The MMC is currently staffed by three assignees from industry and one from national laboratories. They serve a term of two years and then return to their institutions. There is little concern over conflict of interest or favoritism by the MMC staff. The objectives of MMC are to: (1) establish the technology of micromachining; (2) disseminate the technology to industry; (3) help industry with the technology; and (4) foster international collaboration in the area of micromachine technology.

MITI and MMC both worked hard to encourage participation by overseas researchers in the national project. However, a number of U.S. firms that applied to be research supporting members (funded to do research) were not able to arrive at mutually satisfactory agreements. Under MITI contracting rules, for example, 50 percent of all royalties resulting from research belong to the Japanese government. Furthermore, all funded participants are required to share some background information with the other participants. AIST is currently reviewing its contracting procedures to find ways to encourage greater international participation in MITI programs. While MMC-funded work is considered precompetitive, foreground rights are 50 percent owned by NEDO. Other Japanese companies that pay taxes may also have access to this information. However, since they lack practical experience, the members do not believe that they can work effectively. All of the equipment purchased with MITI funds is owned by NEDO and "is returned to the government when the project is complete."

The project is designed so that the first five years will be used to investigate its research requirements. During this phase, changes to the project can be proposed to MITI. After the first five years, the project will be evaluated. MMC will use an external evaluation team that will be chaired by a representative from industry and will consist of representatives from universities, industry (producers and suppliers), and government. NEDO, AIST, and the Technology Committee of MMC will also review the project. AIST will not only evaluate the program's technical goals, but also the project's effectiveness in attaining national goals. MMC's schedule for implementation and evaluation of its program is shown in Figure 7.10.

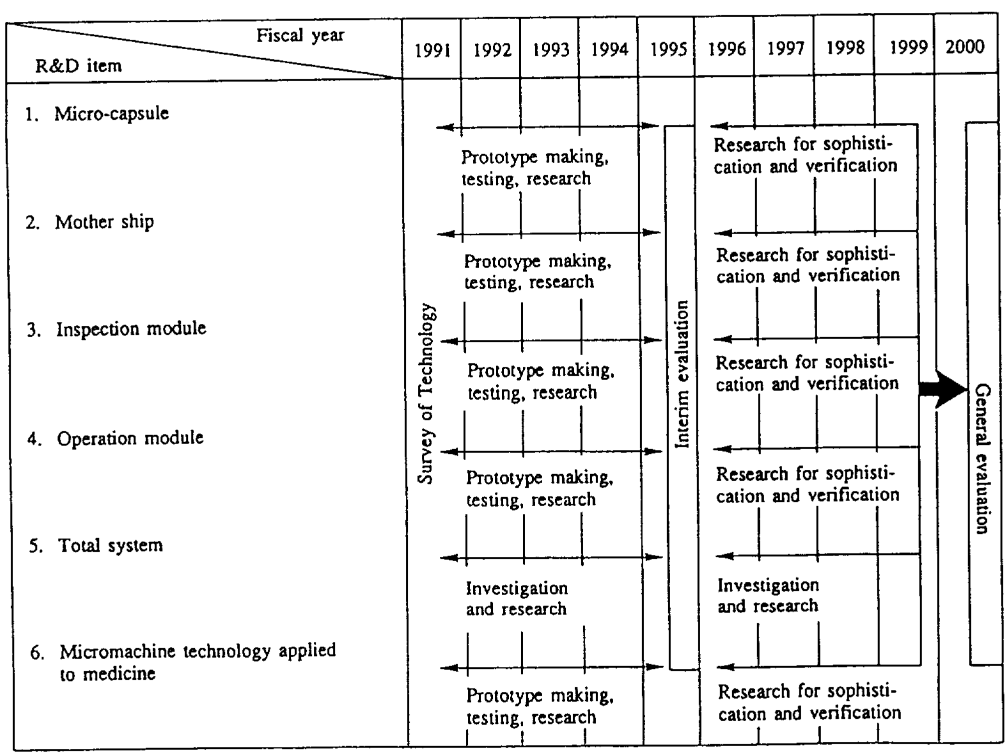


Figure 7.10. MMC program schedule.

AIST evaluates projects on a two-tier basis: (1) management/supervisory -- whether there was an appropriate use of tax monies, a budget analysis, and so forth; and (2) technical evaluation -- whether goals were achieved. AIST is also considering another metric for this program -- methodology/metrology for evaluation. This would address the most fundamental question of what constitutes success on the micron level.

The national micromachine program is structured to develop the base technology for MEMS. It has a very wide definition of MEMS, with only 15 to 20 percent of the research in silicon IC technology. The program relies on the companies to determine any real applications for the technology and to develop commercial products for that market. The program ensures that there is a focus project, and that the project is broad enough to explore many avenues of the MEMS arena. MITI encourages the start of a program before the final goal is really well understood or in some cases well defined. MITI appears to rely on revisiting those goals during the first half of the program, and refining the objectives as more knowledge and information is obtained.

The communication infrastructure in Japan is excellent, both in its formal and informal aspects. It appears that the effort made by MITI to involve as large a number of institutions and professionals as possible in its programs has fostered a very effective informal network.

Japanese prefectures are also very active in forming and funding institutions (e.g., KAST) that support work in MEMS. These institutions actively allow companies to work there using equipment developed by other companies. An example is the microcar that was built at KAST on a Toshiba machine by a Nippondenso employee (Teshigahara, Hisanaga, and Hattori 1992).

Universities in Japan do not provide stipends to graduate students to the extent that U.S. universities do. Japanese universities encourage companies to send their engineers and scientists to the universities to do graduate work. In most cases, the scientists and engineers work on company-related issues. The United States has very limited situations where this is done.

The Japanese national university system is in the process of establishing Nagoya as a center for micromachining. This will cause the reorganization of departments, resulting in a strong focus on micromachining. Thus, there are at least two Japanese government agencies (MITI and the Ministry of Education) involved in funding MEMS research at a national level, in addition to efforts by local prefectures and private companies.

Similarly, several different U.S. Government agencies have recognized the importance of MEMS and are involved in funding this field. The National Science Foundation (NSF) was instrumental in advancing MEMS by establishing an Industry/University Cooperative Research Center (I/UCRC) at the University of

California/Berkeley. The mission of this center is to develop a science and engineering base for microsensors, microactuators, mechanical microstructures and microdynamic systems. NSF has also provided support for student attendance at conferences. The NSF's I/UCRC program may be funded by both government and industry in a membership format. In most cases, there are no long-term commitments by companies, and typically funding is reviewed on an annual basis. Other government agencies, including the Advance Research Projects Agency, National Institutes of Health, and Department of Defense, have supported MEMS work at universities to support their specific needs, and have also supported student attendance at conferences. Through these and other activities, an infrastructure has been established in the United States to exchange information, develop generic techniques for MEMS, and train students. Coordination of U.S. Government efforts in MEMS comes about through informal networking of program managers at individual agencies.

Most of the effort in the United States has been directed toward IC silicon-based MEMS and some LIGA. There has been no effort in what the Japanese would call "milli" or conventional machining.

The professional engineering societies have been extremely supportive of MEMS work. They established the first workshop on solid state sensors and actuators, and held the first MEMS conference. Both of these conferences have become ongoing activities (involving students and researchers from the United States, Japan, and other countries) that allow for exchange of information among those active in the MEMS field. Many of those first students are now active professionals in the field.

Government agencies have been very active in promoting cooperative research between industry and universities. The I/UCRC program requires that the bulk of funding comes from outside of NSF. Conversion monies, those redirected from national defense, require that a commercial goal be established. MEMS in the United States has been very product oriented. Products have come from large companies and small companies, as well. The concept of a foundry system is receiving government support as a way to expedite the availability of facilities to more universities and companies. This should allow for faster development of concepts and devices.

The other area being supported by the U.S. Government is the CAD area for MEMS. To be able to do MEMS modeling requires the ability to do both mechanical and electrical simulation. The present quality of MEMS modeling is one of the major hindrances, for all involved, to fast commercialization of MEMS devices.

REFERENCES

Higuchi, T., Y. Yamagata, and K. Kudoh. 1990. "Precise Positioning Mechanisms Utilizing Rapid Deformations of Piezoelectric Elements." In *Proc. IEEE MEMS 1990 Workshop*, pp. 222-226.

Morikawa, T., Y. Nonomura, K. Tsukuda, M. Takeuchi, A. Honsono, and M. Kawai. 1993. "3-Dimensional Piezoresistive FEM Analysis for a New Combustion Pressure Sensor." In *Transducers '93*, pp. 598-601.

Sampsell, J.B. 1993. "The Digital Micromirror Device and its Application to Projection Displays." In *Transducers '93*, pp. 24-27.

Teshigahara, A., M. Hisanaga, and T. Hattori. 1992. "Fabrication of a Shell Body Microcar." In *Proc. Third International Symposium on Micro Machine and Human Science*, pp. 137-141.

APPENDICES

APPENDIX A. PROFESSIONAL EXPERIENCE OF PANEL MEMBERS

Kensall D. Wise (Chairman)

Dr. Wise received his Ph.D. in Electrical Engineering in 1969 from Stanford University. From 1963 to 1965 and from 1972 to 1974, he was a member of the Technical Staff at Bell Telephone Laboratories. In 1974, he joined the Department of Electrical Engineering & Computer Science at the University of Michigan. His present research interests focus on the development of solid-state sensors for applications in health care, transportation, environmental monitoring, and industrial process control. He served as General Chairman of the 1984 IEEE Solid-State Sensor Conference, as Technical Program Chairman of the 1985 International Conference on Solid-State Sensors and Actuators, and as IEEE-EDS National Lecturer for 1986. He is a Fellow of the IEEE, and has served on many program committees for the International Electron Devices Meeting, the International Solid-State Circuits Conference, and the International Conference on Solid-State Sensors and Actuators.

Joseph M. Giachino

Mr. Giachino received his B.S. degree in Engineering Physics and his M.S. degree in Physics from New York University. He is currently Program Manager, Sensor and Actuator Technology, in the Sensor Business Resource Center of the Electronics Division of the Ford Motor Company. He has experience in research and development; product engineering; and manufacturing of sensors and actuators for radiation detectors, process control systems, and automotive control systems. In 1981, he received the Henry Ford Technology Award for the development of pressure sensors for electronic engine control. Prior to joining Ford Motor Co., Mr. Giachino was at Teledyne Isotopes and Babcock & Wilcox. He has fourteen U.S. patents, and has published numerous articles. He is a member of Tau Beta Pi, IEEE, American Ceramic Society, and ISHM. He has served as Vice President of the Industrial Electronics Society of IEEE, Associate Editor of *Industrial Electronics and Control Instrumentation Transactions* of IEEE, and is a member of the Solid State Sensor and Actuator Workshop of the Electron Devices Society of IEEE.

Henry Guckel

Dr. Guckel received his Ph.D. in Electrical Engineering from University of Illinois in Urbana in 1963. He joined IBM Research in Yorktown Heights to work on high-speed computers. He became a member of the electrical engineering faculty at the University of Wisconsin in 1970, and is currently the IBM-Bascom Professor. He is the founder of the Wisconsin Center for Applied Microelectronics. His research interests extend from microelectronics to micromechanics, with special emphasis on surface micromachined sensors, and micromagnetics via deep X-ray lithography. He is active in international affairs, has published extensively, and is named on twenty patents.

Benjamin Hocker

Dr. Hocker is responsible for identifying new center directions and strategies in sensor technology and product applications. He has eight years of experience heading technology groups responsible for the development of new technology in solid-state sensors, chemical sensors, and indoor air quality emphasizing sensors based on silicon integrated circuity technology, thin films, and micromachining. He has been involved in fiber-optic acoustic sensors, magnetometers, proximity sensors, and fiber-optic data distribution systems. Before joining Honeywell, he was on the faculty of the Department of Electrical Engineering at the University of Minnesota. He has authored over twenty papers and has three patents, with several others pending. He was general chairman in 1990 and program chairman in 1988 for the IEEE Solid State Sensor and Actuation Workshop; a member of the Committee for the International Solid-State Sensors Conferences in 1987 and 1989; and has been a member of the International Steering Committee on Solid-State and Actuators since 1990.

Stephen C. Jacobsen

Dr. Jacobsen received his B.S. degree in 1967 and his M.S. degree in 1970 from the University of Utah. He received his Ph.D. in 1973 from the Massachusetts Institute of Technology, then returned to Utah to establish the Center for Engineering Design (CED). He has been a key innovative influence in the CED's activities, including: (1) biomedical systems such as high performance prosthetic limbs, iontophoretic drug delivery systems, artificial kidneys, and peritoneal access implants; (2) dexterous robots; (3) entertainment robots; (4) teleoperations systems; and (5) microelectromechanical systems. He also holds appointments in the Bioengineering, Computer Science, and Surgery Departments at the University of Utah. He holds over 45 U.S. and foreign patents, has authored over 120 publications, and has received awards for system design and innovation. He is a member of the National

Academy of Engineering and the National Institute of Medicine, and is a senior adviser at Sarcos Research Corporation.

Richard S. Muller

Dr. Muller received his M.E. from the Stevens Institute of Technology, the M.S. (electrical engineering) and Ph.D. from the California Institute of Technology. He is a Professor of the Electrical Engineering Department, and one of two founding directors of the Berkeley Sensor & Actuator Center (an NSF/Industry/University Cooperative Research Center). He has been awarded NATO and Fulbright Research Fellowships at the Technical University, Munich, Germany, and in 1993 he received the Alexander von Humboldt Senior Scientist Research Award. He is a member of the National Academy of Engineering of the United States, a Fellow of the IEEE, Chairman of the Sensors Advisory Board, and a Member of the Advisory Committee for the Electron-Devices Society of IEEE. He has chaired the steering committee for the biennial Transducer Conference, and served as General Chairman of TRANSDUCERS '91. He is the coauthor of *Device Electronics for Integrated Circuits* (2nd edition, Wiley 1986) and coeditor of *Microsensors* (IEEE 1990). He is author or coauthor of more than 200 technical papers and of 15 patents.

APPENDIX B. PROFESSIONAL EXPERIENCE OF OTHER TEAM MEMBERS

Geoffrey M. Holdridge

Mr. Holdridge is Staff Director of the WTEC/JTEC Program, funded by the National Science Foundation under a grant to the International Technology Research Institute at Loyola College in Baltimore, Maryland. He manages the day-to-day affairs of the JTEC and WTEC programs at ITRI. Prior to coming to Loyola in 1989, he served as a Special Assistant to the Division Director for Emerging Engineering Technologies (EET) at NSF, where he helped manage the JTEC program at NSF. In a special assignment for the EET Division in 1987-88, he prepared a report on the long-term industrial consequences of a loss of U.S. competitiveness in the memory chip market as part of NSF's contribution to an inter-agency study on the status of the U.S. semiconductor industry. Mr. Holdridge has also worked as Staff Consultant for the National Academy of Sciences' Panel on the Impact of National Security Export Controls in International Technology Transfer (also known as the Allen Panel). He holds a B.A. in History (specializing in 20th Century East Asia) from Yale University.

Linton G. Salmon

Dr. Salmon recently completed a tour as the director of the solid state and microstructures program for the National Science Foundation. In that capacity, he directed NSF funding of research in electronic materials, semiconductor manufacturing, advanced processes, electronic packaging, and microelectromechanical systems. Dr. Salmon came to NSF from Brigham Young University, where he has now returned to his position as Associate Professor. His current research interests include MEMS applications and packaging, multichip module packaging, and high-speed VLSI integrated circuits. Previously, he was Director of GaAs Engineering at Rockwell International, where he directed the development of advanced designs and processes for III-IV integrated circuits and multichip packaging. Earlier he was head of GaAs Technology and Molecular Beam Epitaxy Sections at Hughes Research Laboratories. He received his B.S. degree in Physics from Stanford University, M.S. degree and Ph.D. in Applied Physics from Cornell University.

Cecil H. Uyehara

Cecil H. Uyehara, President of Uyehara International Associates, is a consultant in the Washington D.C., area on U.S.-Japanese relations (science and technology). He served in the U.S. government for almost twenty-five years with the Air Force (weapons systems planning), the Office of Management and Budget (military assistance), and the Agency for International Development (AID). He has published works on Japanese politics, scientific advice and public policy, and Japanese calligraphy. He organized the first U.S. Congressional hearings on Japanese science and technology, lectures at the U.S. Foreign Service Institute on Japanese science and technology, and served as a consultant to the Yomiuri Shimbun and to the Library of Congress on Japanese calligraphy. He received his B.A. degree from Keio University (and his M.A. degree from the University of Minnesota, both in Political Economy, and has received awards and grants from the Ford Foundation, American Philosophical Society, University of Minnesota (Shevlin Fellowship) and the National Institute of Public Affairs.

Site:	**AIST/MITI Headquarters** **1-3-1, Kasumigaseki** **Chiyoda** **Tokyo 100, Japan**
Date Visited:	September 27, 1993
Report Author:	J. Giachino

ATTENDEES

JTEC:

J. Giachino
H. Guckel
B. Hocker
G. Holdridge
S. Jacobsen
R. Muller
L. Salmon
C. Uyehara
K. Wise

NSF:

Larry Weber	National Science Foundation (Japan)

HOSTS:

Hiroshi Kasai	Director, Machinery & Aerospace R&D
Satoshi Ito	Senior Researcher, Machining Technology Div. Manufacturing System Dept. Mechanical Engineering Laboratory

BACKGROUND

The role of the Ministry of International Trade and Industry in promoting the industrial and technological competitiveness of Japan goes back at least to the early part of this century, but its role has been changing dramatically in this decade. MITI policy now focuses on international contribution and cooperation. The Agency for

Industrial Science and Technology was formed within MITI in 1948 to manage a number of government laboratories and institutes (some of which have a history dating as far back as the late 19th Century). Since 1964, AIST has been involved in the promotion of R&D projects through government-private sector cooperation. This has been carried out through a series of national projects, the earliest of which (1966) was dubbed the "Large-Scale Project (National R&D Program)." Several such projects (e.g., Moonlight Project, Basic Technologies for Future Industries, etc.) are underway at any given time; under each project are specific R&D programs.

In 1991, MITI established a program to develop micromachine technology under the auspices of the Large-Scale Project. Since then, the Large Scale Project has been restructured into the "ISTF" (Industrial Science & Technology Frontier Project) and the project has been reoriented toward basic research. Thus, MITI's Micromachine Technology Project that is of interest to this panel is one of several programs funded under this new ISTF Project.

MITI's NATIONAL R&D PROGRAM ON MICROMACHINES

Structure of Program

MITI's micromachine technology R&D program was initially budgeted in 1991 as a ten-year program with total projected funding of ¥25 billion. The first five-year phase of this was projected at ¥10 billion, to be followed by an interim evaluation period and a second five-year phase budgeted at ¥15 billion.

Our host, Mr. Kasai, stressed that these funding figures are targets. In fact, the 1993 AIST brochure (handed to the panel) shows a total of ¥2.43 billion actually allocated to the micromachine program in its first three years of funding. Mr. Kasai also said that only 10-25% of the total micromachine budget is devoted to research on approaches to micromachine construction that employ semiconductor lithography and related technologies, which are the focus of this study.

The structure of this program is shown in Figure 7.8 (p. 112). As indicated in the figure, three national laboratories are funded directly by AIST under this program: the Electrotechnical Laboratory, the Mechanical Engineering Laboratory, and the National Research Laboratory of Metrology. Industrial participation in the program is managed through the New Energy and Industrial Technology Development Organization (NEDO) under AIST. NEDO in turn contracts with the Micromachine Center for the management of the individual research projects. As shown in Figure 7.9 (p. 113), MMC funds 23 Japanese companies and one Japanese Institute to perform R&D under this program, as well as one U.S. company, one U.S. non-profit and one Australian university. All 27 of these are considered "research supporting" members. Each research supporting member pays a membership fee which is used to pay MMC's overhead. The JTEC panel learned later that MMC also is considering other uses for these membership fees (see site report on MMC by Linton Salmon -- p. 158).

APPLICATIONS

Under the two-phase approach MITI has adopted for this program, the first five years will be devoted to the development of enabling technologies through a program focus on one or more "model" applications, which may or may not turn out to be realistic. The results of these model application studies and the technologies developed in support of them will be evaluated after five years. The current model will be reviewed and R&D targets will be established for the second five-year phase.

The focus of this program is on applications development, without any commercial level consideration of fabrication approaches. Thus it is not surprising that only a relatively small percentage of the effort is being devoted to semiconductor lithography-based approaches.

The JTEC team's AIST hosts made it clear that they are looking for new ideas for practical applications of micro-machines, as well as new mechanisms for seeking out new applications ideas. The ISTF handout MITI provided to the panel listed "determination of appropriate applications" as a key future subject for the micromachine program. One idea mentioned by Mr. Kasai is the exchange of information and ideas among individual researchers, regardless of seniority, for their ideas on applications. This would be in keeping with MITI policy making, since MITI programs traditionally have been advised by informal committees composed of a variety of outsiders.

Power Plant Application

In March 1993, AIST selected its first model application for development under the MITI program: an advanced maintenance system for heat exchanger tubes in electric power plants (Figure 6.5, p. 84). This system is envisioned as consisting of several miniature robots: a "mother ship" capable of traversing the inside of pipes of 10 mm diameter (Figure 7.2, p. 108); a "microcapsule" of 2 mm diameter (Figure 7.3, p. 108) that would float on the coolant stream in smaller pipes, detecting cracks or corrosion on inside pipe walls; a wireless "inspection module" (Figure 7.4, p. 109) of 2.5 mm diameter that would move through heat exchanger pipes with an inching worm drive mechanism; and an "operation" or "work" module (Figure 7.5, p. 109) that would repair flaws detected by the microcapsule and the inspection module.

The mother ship carries the inspection modules and operation modules close to the portion where something is wrong. Then the mother ship supplies power to both modules and transmits the information. To develop this micromachine, R&D will be carried out on: electrostatic driving mechanisms, optical scanners, pneumatic clampers, microbatteries, coupling mechanisms, and group control and behavior control systems. The microcapsule, floating on the stream in the pipes, detects cracks or scales on the inside of the pipe's wall and reports the location to the control center. This will require R&D on: microdynamos, steering mechanisms, microgyroscopes, flaw detectors, and signal transmitters. The wireless inspection module travels from the mother ship to the portion where something is wrong. Then it precisely inspects and analyzes the condition of the changes and reports the results to the control center using the mother ship. For this micromachine, R&D will be needed on: inching worm driving mechanisms, piezoelectric motion drive devices, CCD microvisual sensors, ultrasonic microsonar devices, microphotospectroscopy devices, and teleoperation and coordination control systems. The operation module travels from the mother ship to the portion where something is wrong. Then it repairs the problem according to the report from the inspection module. R&D will is underway for this machine: gear train locomotion mechanisms, multi-degree of freedom manipulators, environment recognition devices, end effectors, photoelectric generators with boosters, high power devices, and valves.

Since the focus of the MITI program in this first model applications phase is on the development of the enabling technologies, perhaps the most significant elements of Figures 6.5 and 7.2 - 7.5 are the key components and technologies that are listed on each figure. As the JTEC panel learned in more detail at MMC, each of these components has been assigned to one or more of the research supporting members of MMC.

It was evident from this presentation that a lot of thought has gone into the powerplant application. Yet our AIST hosts stressed that final specifications of these devices (listed in the figures referred to above) have yet to be determined. Furthermore, by designating this only as a "model" application, AIST recognizes that it is quite possible, if not likely, that this system will never actually be built.

Research related to this model application is supported in part by the Japanese government's electricity use tax.

Medical Application

AIST is in the process of developing a similar concept plan for a biomedical model application, tentatively dubbed "Intraluminal Diagnostic & Therapeutic System." This concept envisions the development of microcatheters in the 1.5 mm diameter range that could be used to treat, for example, cerebral aneurisms and/or blockages of the pancreatic bile duct. Figure 6.6 (p. 85) shows the general concept of this application. Figures 7.6 and 7.7 (p. 111) are conceptual drawings of the outer duct and the inner duct of such a catheter, respectively. According to some of the literature handed to the visiting JTEC team, this application is not as far along in development as is the power plant application. Mr. Kasai stated that this application is now in the final stages of concept development.

Possible Future Application – Targeting Energy Savings

AIST is now considering the possible addition of a new model application targeted at energy savings in manufacturing. As one example, Mr. Kasai cited the large amounts of energy that are required to construct and maintain big clean rooms for semiconductor manufacturing. He expressed the hope that energy could be saved through the development of microrobots that could aid the manufacturing and assembly of semiconductor devices in clean room facilities substantially smaller than those commonly used. It became evident during the JTEC team's visit that our hosts are just now beginning to flesh out this idea.

EVALUATION TECHNOLOGY

AIST is considering a new initiative aimed at addressing the question of how to evaluate the performance of micromachines. Prof. Miura of the University of Tokyo will head up a committee to consider these "evaluation technologies" (metrology issues).

INTERNATIONAL PARTICIPATION

As listed in Figure 7.9, one U.S. company, one U.S. non-profit organization and one Australian university are involved in the micromachine program. Later at MMC, the JTEC team learned that Karlsruh in Germany is also participating in this program, though not as a research supporting member.

MITI initially announced this program as an international effort, and went to some lengths to encourage participation by overseas researchers. However, a number of U.S. firms that did apply to participate as research supporting members (i.e., to be funded to do research) evidently were not able to work out contractual arrangements with MITI that were mutually satisfactory. Under MITI contracting rules, for example, 50% of all royalties resulting from research funded by MITI belong to the Japanese government. Furthermore, all funded participants are required to follow the Japanese governmental budget control systems. During discussion, Mr. Kasai mentioned that AIST is currently reviewing its contracting procedures in an effort to find ways to encourage greater international participation. Professor Wise, the JTEC Panel Chair, mentioned during this discussion that there is a need to share information internationally on the properties of new materials used in MEMS devices. Mr. Kasai responded that AIST would consider requests for information sharing on a flexible case-by-case basis. Mr. Kasai also mentioned that he will be representing Japan at an international conference in October 1993 to find ways of carrying out the International Advanced Robotics Program that was agreed to, in principle, at the Versailles Summit.

QUESTIONNAIRE

Following are answers to questions submitted by the JTEC team prior to their visit. Mr. Kasai stated that only the "management" questions posed by the JTEC panel apply to AIST. [A complete list of questions posed by the panel is included in the Yaskawa Tsukuba Research Laboratory site report, pp. 225-236.]

F.12. How much funding is being directed into MEMS research and development in your organization? What percentage is this amount of the total R&D budget?

AIST does not have the necessary statistics to answer this question. However, AIST estimates that, within the 23 Japanese companies participating in funded research, there are 270 researchers working on micromachines, of which approximately 190 are funded by the Japanese national government.

Based on an informal telephone survey, AIST estimates that a number of large Japanese companies participating in AIST's micromachine program have very minor internal R&D activities in this area -- *outside of* their normal semiconductor R&D programs which include substantial efforts in silicon micromachining and their contributions to the AIST program. One company estimated its expenditures in the neighborhood of ¥200 - ¥300 million per year.

F.20. The first generation of university graduates who specialized in MEMS are now finishing their degrees. Are employment opportunities for these students plentiful in Japan?

Japanese companies hiring students out of university programs are not looking for specific skills (i.e., MEMS fabrication expertise); they hire for lifetime careers, and are looking for bright young people with general technical skills who can be trained to learn whatever is needed for the wide variety of specific projects they may get involved in at the company during their careers.

G.7. Are you involved with joint development with other organizations? What kind (other companies, universities, foundations, etc.)?

AIST can only cite examples from its own experience (see text above); AIST is not aware of all the cooperative efforts of the many companies involved in the micromachine program with the other project. National laboratories funded under AIST also have their own cooperative activities with individual companies, inside and outside the purview of the MITI program.

A.12 Are room-temperature superconductors being explored, and if so, what materials and processing techniques are being used?

The micromachine program is not involved in room temperature superconductivity R&D. However, there are other MITI programs that do fund such research, including some that are involved in research in micromachining of such materials. The Sunshine Project also has some related activities -- e.g., wire fabrication for use in superconducting energy storage coils. Prof. Fujita of the University of Tokyo is also working in this area. [The Atom Technology (i.e., nanofabrication) program is listed in the 1993 AIST brochure. According to Mr. Kasai, the micromachine program and the atom technology program are two of the newest ISTF programs at AIST, and are getting favorable budgetary treatment compared to other programs. Yet the micromachine program has not been fully funded. Mr. Kasai mentioned earlier that loss of tax revenues due to the Japanese recession has directly affected his program's budget.]

DISCUSSION

Question: Does the power plant application apply to nuclear plants?

Kasai: Yes, in principle, but remember that this is not an actual application -- just a vehicle to stimulate development of basic enabling technologies for future (real) applications.

[Mr. Kasai went on to explain that AIST's mission is to stimulate development of generic technology -- Japanese companies are expected to develop and market real applications after the termination of the micromachine project.]

Question: How are projects evaluated?

Kasai: [There is a] two-tier approach:
1. Management/supervisory (what's appropriate use of taxpayers funds, budgetary analysis, etc.)

2. Technical evaluation (were technical goals achieved?, etc.)

As mentioned before, AIST is now considering a third tier: methodology/metrology evaluation (e.g., how do you measure success in a micron scale device?)

Jacobsen: Who owns the equipment? Can companies use facilities funded by AIST to work on a specific product?

Kasai: All equipment is owned by NEDO. When a project is completed, the equipment is returned to the government. MMC research is only "pre-competitive." Conversely, AIST has asked Nippondenso for use of its airbag sensor technology as a base for development of the MMC project!

Wise: Is technology developed at each company under MMC funding available to all companies participating?

Kasai: "Foreground" rights are 50% owned by NEDO. Participants creating foreground [rights have] the other 50%. Other Japanese companies that pay taxes may also have access; but as non-members, they have to pay 100% usage fee for those foreground [rights].

[Mr. Kasai explained further. The final criteria for evaluating the micromachine program will be as follows: (1) Did it develop useful technologies and concepts? and (2) Management criterion: is it bottom-up technology?]

Holdridge: Is there a way to count resources in other MITI/AIST research programs that are relevant to MEMS?

Answer: Basically no.

Question: Are there formal evaluation meetings?

Answer: Yes. Constant evaluation [is being] carried out by NEDO and AIST. Final decisions on allocation of research funding are made by AIST in consultation with NEDO.

Site: **Canon Inc.**
5-1 Morinosato-Wakamiya
Kanagawa 243-01, Japan

Date Visited: September 29, 1993

Report Author: S. Jacobsen

ATTENDEES

JTEC:

S. Jacobsen
R. Muller
C. Uyehara

HOSTS:

Dr. Ichiro Endo	Director
Dr. Minami	General Manager
Dr. Nakagiri	Senior General Manager
Dr. Hirai	Senior Engineer

NOTES

The JTEC panel's hosts were kind and made extensive presentations. In addition, they provided team members with a tour of their facilities. Unfortunately, due to the limited time allowed for each site visit, panelists were only able to see the basement and roof floors of the facility. The facilities observed were excellent. There was apparently sufficient funding to meet their needs.

Canon's gross sales are approximately ¥10 billion, with 80 percent of sales in business machines and 20 percent in cameras.

Five areas of interest were discussed during the presentations. The first was advanced materials and super lattices. Work in this area included Langmuir Blodgett films (LBF), gallium arsenide (GaAs), superfine particles, and superconductivity. The second area discussed was optical systems, which included optoelectrons, multimedia, and local area nets (LAN). The third area was nanometer scale systems. Canon has efforts in scanning tunneling microscopy, AFM, and MM. Another area of interest was E-beam lithography, which included work on sources and optics.

The final area discussed was studies in bioremediation, which was aimed at disposal of used produce, ecology maintenance, and environment controls.

Strategies were discussed for three areas:

1. Materials: piezoelectric materials, LBF, superconductivity, and gal areas
2. Process: photo and E-beam lithography, bonding, etching, and deposition
3. Packaging: hybrid, monolithic, and chip mounting.

It is anticipated that Canon's efforts will lead to device design in the areas of sensors, actuators, and systems.

Canon representatives emphasized the fact that a very important issue was technomix to obtain intelligent MEMS, not just direct work on silicon micromachining alone. They also noted that MEMS were too small for business machines, but would be adequate for sensors.

Canon has established ten development targets:

1. X-ray exposure stepper, which is being constructed in a basement lab
2. Langmuir Blodgett films
3. Systems to allow recycling of products such as toner cartridges
4. Microfluidics for sensor and fluid processing systems
5. Solar cells -- amorphous silicon systems based on their past work with amorphous Silicon. They mentioned problems with recycling. Canon is engaged in a joint project with an American company.
6. Biotechnology
7. Piezoelectric actuation systems
8. Si to Si fusion bonding
9. Anodic bonding was discussed, but in the context of residual strain problems.

Site: **Hitachi Center for Materials Processing Technology**
Mechanical Engineering Research Laboratory
502 Kandatsu, Tsuchiura
Ibaraki 300, Japan

Date Visited: September 29, 1993

Report Author: K.D. Wise

ATTENDEES

JTEC:

H. Guckel
K.D. Wise

HOSTS:

Dr. Toshihiro Yamada — Head, Center for Materials Processing Technology

Dr. Kazuo Sato — Senior Research Scientist, Center for Materials Processing Technology

NOTES

Dr. Toshihiro Yamada welcomed the JTEC team to Hitachi and explained the general organization of the Center for Materials Processing Technology and its involvement in MEMS. Four operating units are involved in the center. They deal with: (1) surface modification, welding, and microbonding; (2) microassembly, ultrafine particle applications, and fine pitch bonding; (3) micromachining and precision forming; (4) and design, manufacturing, and assembly. The ultrafine particles are 0.1 μm silicon dioxide and have been applied to enhance images by creating uniform dispersion patterns. Dr. Kazuo Sato then described the work in the third unit in greater detail, and provided reprints of recent articles.

He first described his work on modeling silicon etch processes and its application to a number of new micromachined device structures (Sato, Koide, and Tanaka 1989; Koide, Sato, and Tanaka 1991). The program is currently functional in 2-D and is being extended to 3-D modeling. In order to obtain the etching coefficients as a function of temperature in all of the silicon crystal planes, hemispherical protrusions and recesses were machined in thick silicon segments and etched for various times in KOH-based etching solutions at temperatures from 40°C to 78°C. The resulting surfaces were then carefully probed to measure the resulting etch rates, which were entered in the program. The first application of this data was in a bulk micromachined accelerometer (Koide, Sato, Suzuki, and Miki 1992), which is intended for automotive systems and will be a product next year. It is a 3.2 mm x 5 mm die built on a symmetrical cantilever etched from both sides of the die. The silicon die is bonded between two glass plates to form a differential capacitor. The symmetrical design eliminates most off-axis sensitivity. The device is mounted with hybrid electronics on a ceramic board about 1 cm on a side. Electrostatic self-test is included. The device is a good example of how a detailed knowledge of bulk etching characteristics can be used with computer-assisted mask optimization to realize a complex device from a rather simple process.

A second project was an atomic force microscope tip formed by using a 200 μm long cantilever whose tip angles over a silicon recess and is realized along the side wall (Hosaka et al. 1992). The tips are sharpened to 20 nm using focused ion-beam technology, and position is read out optically. The probe is made of silicon dioxide and for magnetic imaging is coated with a thin film of cobalt. A third project involved the use of isotropic silicon etching to create acoustic lenses (Hashimoto et al. 1993) for scanning acoustic microscopes from 4 to 6 mm-thick silicon stock wafers. Cavities 80 μm in diameter were etched with a sphericity of better than 0.2 μm, and the edges of the wafer were then beveled back by grinding. The devices could image 1 μm lines and spaces at 944 MHz. A variety of devices have been realized.

The microvalve presented at Transducers '93 (Shikida et al. 1993; Sato and Shikida 1992), based on the electrostatic attraction of a thin silicon membrane held between two plates (one containing an orifice), was described. The film was permalloy, chosen because of its availability and mechanical characteristics. The current device measures 25 mm x 25 mm, but could be miniaturized considerably. It was operated at 70 V. The device is innovative and impressive in that it operates across a gap of 2.5 mm and yet seals well, apparently without sticking. It is aimed at gas flow control at low pressures as in semiconductor manufacturing. A silicone resin is used to hold and space the two wafers.

Dr. Sato then described work on systems for cell sorting and blood studies that they have developed (Sato et al. 1990; Kikuchi et al. 1992). In the former project, a matrix of 1,584 microchambers is formed in a silicon wafer. Techniques for loading each of these chambers (en-batch) with paired cells have been developed using suction applied through small holes in the back of the chambers, and the cells can then be fused using electrical pulses applied from electrodes imbedded in the chambers. The latter project (Sato and Shikida 1992) produced interesting data on fluid flow in small micromachined microchannels. For example, the flow in a V-groove approximately 8 μm wide across the top was equivalent to about 60 pl/sec/mm at a pressure of 10 cmH_2O.

The Hitachi work under the national (MITI) micromachine program is aimed at a miniature hydraulic rotor pump produced using electron discharge machining. It has produced pressures to 10 atm. In the laboratory, the panel observed an interesting system for low-temperature bonding based on the use of an argon ion-beam cleaning of the surfaces followed by joining. For example, the system has been used to bond piezoelectric ceramics to FeNiCo alloys with a InPb intermediate at 120°C. The system has been used to remove surface oxides from metals, allowing metal-to-metal seals, and is now being tried with silicon-to-silicon structures. Such a system could be of great benefit in the creation of a wide variety of microstructures.

There was considerable discussion of MEMS challenges. Hitachi has not gotten into LIGA even though the company has strong interest in it. Problems cited included a lack of polymer knowledge and lack of an X-ray source (and the associated up-front investment required). Hitachi also was concerned about the patent situation in this area. It was agreed that there is a real need for batch-fabricated and batch-assembled millimechanics, with the feeling that "batch will have more impact than miniaturization." Most of the actuators discussed were electrostatically-driven; the electronics for most devices were hybrid, and it did not appear that Hitachi was strongly pursuing monolithic integration of readout circuitry directly on the transducer chips.

REFERENCES

Hashimoto, H., S. Tanaka, K. Sato, I. Ishikawa, S. Kato, and N. Chubachi. 1993. "Chemical Isotropic Etching of Single-Crystal Silicon for Acoustic Lens of Scanning Acoustic Microscope." *Japan J. Appl. Phys.* 32, May: 2543-2546.

Hosaka, S., A. Kikukawa, Y. Honda, H. Koyanagi, and S. Tanaka. 1992. "Simultaneous Observation of 3-Dimensional Magnetic Stray Field and Surface Structure Using New Force Microscope." *Japan J. Appl. Phys.* 31, July: L904-907.

Kikuchi, Y., K. Sato, H. Ohki, and T. Kaneko. 1992. "Optically Accessible Microchannels Formed in a Single-Crystal Silicon Substrate for Studies of Blood Rheology." *Microvascular Research.* 44: 226-240.

Koide, A., K. Sato, and S. Tanaka. 1991. "Simulation of Two-Dimensional Etch Profile of Silicon during Orientation-Dependent Anisotropic Etching." *Proc. IEEE MEMS '91.* Pp. 216-220.

Koide, A., K. Sato, S. Suzuki, and M. Miki. 1992. "Multistep Anisotropic Etching Process for Producing 3-D Accelerometers." *Digest 11th Sensor Symposium.* Pp. 23-26.

Sato, K., A. Koide, and S. Tanaka. 1989. "Measurement of Anisotropic Etching Rate of Single-Crystal Silicon to the Complete Orientation." *Digest JIEE Technical Meeting on Micromachining and Micromechatronics.* IIC-89-30, pp. 9-17.

Sato, K., and M. Shikida. 1992. "Electrostatic Film Actuator with a Large Vertical Displacement." *Digest IEEE MEMS '92.* Pp. 1-5.

Sato, K., Y. Kawamura, S. Tanaka, K. Uchida, and H. Kohida. 1990. "Individual and Mass Operation of Biological Cells Using Micromechanical Silicon Devices." *Sensors and Actuators.* A21-23: 948-953.

Shikida, M., K. Sato, S. Tanaka, Y. Kawamura, and Y. Fujisaki. 1993. "Electrostatically-Actuated Gas Valve with Large Conductance." *Digest Int. Conf. on Solid-State Sensors and Actuators.* Pp. 94-97.

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Date Visited: September 28, 1993

Report Author: J. Giachino

ATTENDEES

JTEC:

J. Giachino
G. Hocker
G. Holdridge

HOSTS:

Dr. Toshiro Higuchi	Ultimate Mechatronics Project
Felix Moesner	Graduate Student

BACKGROUND

Kanagawa Prefecture, which has an economy equal to that of Korea, provides funding for the Kanagawa Academy of Science and Technology (KAST) to develop a "center of excellence" for the prefecture. The results acquired in research activities will be open to the public in and out of Japan. Royalties from patents will be shared equally between the inventor and KAST.

Dr. Toshiro Higuchi is the project leader of the Ultimate Mechatronics project, a five-year project funded at $10 million, which provides equipment and supports seven researchers. In addition, there are four graduate students from the University of Tokyo who receive no salary from the prefecture, and thirteen researchers from industry. The companies pay the researchers' salaries and a small fee to allow them to work in the laboratories.

The project proposes to develop revolutionary machines to operate under extreme conditions (vacuum and cryogenic), and to pursue the limits of performance of mechatronics technology and its applications in industry. Staff members at the Ultimate Mechatronics project are conducting research to develop muscle-like electrostatic actuators, microrobots, and noncontact wafer transport systems.

The laboratory is in a new building with state-of-the-art equipment. There is adequate space to contain growth without affecting existing projects.

RESEARCH ACTIVITIES

Dr. Higuchi is a mechanical engineer who approaches MEMS from the standard mechanical arena. His laboratory does no silicon wafer work. Dr. Higuchi believes that MEMS is a much wider field than just silicon. He defines a MEMS machine not by size, but by whether one can achieve the desired function solely by using small structures, even if the machine itself is large.

Dr. Higuchi believes that the next technical problem for MEMS is the assembly of small structures. His group is developing a flexible manufacturing system that includes assembly. A prototype is expected in a year. One of Dr. Higuchi's novel concepts is to leave the machined parts on the spindle and assemble the spindles.

Dr. Higuchi wants to show that conventional machine tools can produce structures with accuracies of microns. His laboratory has a machine built by Toshiba that has four axes, is numerically controlled, and is capable of resolution to 1 nm using holography (Egawa, Niino, and Higuchi 1991). The machine, which conducts grinding and lathe-turning operations, was used by a Nippondenso employee working at the laboratory to produce the die for the body of a microcar.

Dr. Higuchi believes that the key technology for micromachining is to have a good actuator guide system for the tool and an accurate feedback system. He believes that future systems will combine many micromachining technologies, including silicon, LIGA, plastic forming, and blanking. Dr. Aoki at Kanagawa University is making a piezoelectric actuated punch press to apply to microblanking.

Dr. Higuchi's research has resulted in a commercial instrument that is used by Prima, a meatpacking company, to fertilize eggs. The instrument uses a piezoelectric vibrating element to avoid deforming the egg, which occurs with conventional methods (Higuchi and Yamagata 1993). The group is working on the injection of DNA into cells.

The laboratory is working to develop an electrostatic actuator by using small efficient cells and stacking them to generate the large force. A demonstration was given in the laboratory of a film actuator (Higuchi, Yamagata, and Kudoh 1990).

Ultimate Mechatronics researchers are working with Toto, a large ceramics supplier in Japan, to develop microparts that work at low temperatures.

Panel members saw a video that demonstrated electrostatic levitation of a silicon wafer. Present systems use optical sensors for closed loop position control. There is a potential that they may switch to capacitive sensors. The video also showed an electrostatic linear actuator that was intended as an artificial muscle.

The laboratory is just setting up an STM. This program will be run by an industrial researcher who will be working on a potential commercial product.

REFERENCES

Egawa, S., T. Niino, and T. Higuchi. 1991. "Film Actuators: Planar, Electrostatic Surface-Drive Actuators." *Proc. IEEE MEMS 1991 Workshop.* Pp. 9-14.

Higuchi, T., and Y. Yamagata. 1993. "Micro Machining by Machine Tools." *Proc. IEEE MEMS 1993 Workshop.*

Higuchi, T., Y. Yamagata, and K. Kudoh. 1990. "Precise Positioning Mechanism Utilizing Rapid Deformations of Piezoelectric Elements." *Proc. IEEE MEMS 1990 Workshop.* Pp. 222-226.

Site:	**Matsushita Research Institute Tokyo Inc.** **3-10-1 Higashimita, Tama-ku** **Kawasaki 214, Japan**
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ATTENDEES

JTEC:

J. Giachino
G. B. Hocker
G. Holdridge

HOSTS:

Dr. Tsutomu Yano	Director, Member of the Board
Koichi Kawata	Statutory Auditor, Member of the Board
Takeo Sato	Senior Engineer
Yoshikazu Kawauchi	Senior Engineer
Hiroshi Ogura	Engineer

RESEARCH AND DEVELOPMENT ACTIVITIES AND DISCUSSIONS

Matsushita is a large electronics and consumer products company founded in 1918, with sales of $47 billion annually, with 43 Divisions and over 200 subsidiary companies worldwide. Its products include televisions, VCRs, and many home appliances sold under familiar brand names such as Panasonic, Technics, and Quasar. Its research facilities include a Central Research Laboratory and Research Centers for Audio Video, Semiconductors, and Living Systems (appliances).

The panel visited the Matsushita Research Institute Tokyo, located in Kawasaki. The institute was founded in 1963 and has 236 employees; 193 are researchers and 22 have doctorate degrees. The institute consists of four laboratories for advanced materials, image processing, human interface, and optoelectromechanics research. The Matsushita corporate level provides 70 percent of the funding for feasibility studies; 20 percent of the funding comes from divisions for specific contract research projects, and 10 percent comes from government-funded research. The latter includes participation in the MITI micromachine program. Eleven to fifteen researchers are working on MEMS technology, depending on one's definition of the field.

The targets of the efforts discussed were fundamental technologies for future micromachines. The work at Matsushita Research Institute on the (MITI) micromachine program involves ultrasonic sensors and rotating wobble motor actuators for the inspection capsule. The main internal efforts at Matsushita in MEMS are in micro electro-discharge machining (EDM). EDM was first developed for metals, and then applied to silicon and other semiconductors. It is viewed as a technique that can join semiconductor processing with conventional machining, providing 3-dimensionality and cylindrical geometry, for example.

Matsushita makes and sells EDM machines commercially. An early machine won an IR100 award in 1985, and the latest ED71 machine with Si micromachining capability won a design award from MITI. This machine, which was developed in conjunction with the Institute of Industrial Science at the University of Tokyo, can form parts with dimensions as small as 5 μm and with 0.1 μm resolution, and sells for about $250,000. Complex shaped parts can be machined; an example was a microturbine of 1 mm diameter with a 0.3 mm shaft.

The EDM machines were shown on a laboratory tour, which also included an STM microscope built in-house and used for materials studies. The institute also described micromolding of parts from a mold fabricated by EDM, along with a shape memory alloy actuator for a hard drive head for noncontact start and stop.

The Central Research Laboratory is looking at materials for magnetic, piezoelectric, and electrostatic actuators for MEMS, including ultrasonic motors. In addition, many sensors are being developed at the Living Systems Research Laboratory. Matsushita would like to replace many conventional sensors with semiconductor-based devices; the major issues are cost and reliability.

Four possible stages of MEMS development were proposed: Sensors comprise the first stage, while the second could be devices that move but are not coupled to the outside world. A third stage would develop actuators coupled to the outside; torques > 1 gm-cm are believed required to be useful. The final stage would involve complete MEM systems. Matsushita researchers believe it is most important now to clarify what systems applications are best suited to MEMS. Molding is seen as key to addressing high-volume applications, perhaps using molds formed by micro electro-discharge machining; parts assembly is another critical need of MEMS technology. The institute is also interested in future LIGA experiments with SORTEC. Some believe that MEMS may represent a series of gradual improvements in making tiny mechanical parts. The benefits may appear in a long, evolutionary rather than revolutionary, fashion.

REFERENCES

Masaki, T. 1990. "Micro Electro-discharge Machining and its Applications." Paper presented at Micro Electro Mechanical Systems, 11-14 February. Napa, CA.

Panasonic Micro Electro-discharge Machine MG-ED07 and MG-ED05 product literature.

Uchida, T., et al. "Molecular Dynamics Simulation of Nanometer-level Cutting."

Site: **MITI**
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Date Visited: September 28, 1993

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JTEC:

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K.D. Wise

HOSTS:

Dr. Kenichi Matsuno	Director-General, Mechanical Engineering Laboratory, AIST/MITI
Dr. Kunikatsu Takase	Director, Intelligent Systems Div., ETL/AIST/MITI
Dr. Yoshihisa Tanimura	Director, Mechanical Metrology Department, Natl Research Laboratory of Metrology, AIST/MITI
Ryutaro Maeda	Sr. Researcher, Mechanical Engineering Laboratory, AIST/MITI
Dr. Yuichi Ishikawa	Sr. Research Officer, Design Engineering Div., MEL/AIST/MITI
Dr. Tatsuo Arai	Director, Autonomous Machinery Division, Robotics Dept., MEL/AIST/MITI

NOTES

Prior to the meeting, Mr. Ryutaro Maeda introduced the schedule for the visit. He mentioned that the Mechanical Engineering Laboratory (MEL) had prepared answers to the questions about MEMS that were raised in preparation for the visit, and provided the JTEC panel with written copies of the answers. Copies of the questions and answers are attached, and include definitions of MEMS and of micromachines.

Dr. Kenichi Matsuno opened the meeting by giving an overview of work in MEL. He pointed out that the overall effort involves 254 personnel, including 207 professional scientists and engineers. This number has been slowly declining due to budgetary constraints, decreasing from 279 in 1989 through attrition. MITI's Micromachine Technology Project is one of eleven Designated Research Projects under the Industrial Science and Technology Frontier Program. These are funded at twice the rate of the Special Research Programs listed as well as a total of forty-six separate Ordinary Research Programs currently under way. The research topics under MEL span a very broad range, dealing with subjects such as energy generation (under the New Sunshine Program), underground space development, air pollution, robotics, properties of materials, bioengineering, and human factors. The total budget for MEL in 1993 is about ¥1.6 billion, of which the eleven programs under the IST Frontier effort are funded at about ¥262 million, or about 16.4 percent of the total for MEL.

Research efforts in micromachine technology in the MEL are focused on developing design and evaluation mechanisms for micromachines, particularly those having moving mechanisms. This involves efforts on complex microprocessing for 3-D structures, including complex micromachining, material modification, and wafer-level bonding. It also involves efforts on micromechanisms (mechanical properties of materials and microtribology) and on micromachine control structures. The micromachining efforts involved microgrinding to dimensions of 50 μm and combinations of microgrinding and electrochemical etching. The laboratory representatives also mentioned efforts to bond ceramics to metals and silicon to metals using ultrahigh vacuum technology, with ion cleaning of the surface followed by pressure-assisted bonding at room temperature. They are exploring the use of focused ion beam technology for microfabrication, and on the evaluation of the mechanical properties of the resulting microstructures. Goals are to modify the mechanical properties (e.g., elasticity) of the materials in favorable ways as well as their etching behavior in order to allow the creation of new structures. Piezoelectrically-actuated microgrippers have been realized for use in microassembly operations. Teleoperated devices have been constructed based on discrete piezoelectric drive elements capable of six degree-of-freedom operation (Arai, Larsonneur, and Yaya 1993; Arai and Stoughton 1992). Strain gauges are mounted on the individual elements and the actuation is keyed off of the sensor outputs (the actuators are slaved to the sensor drive signals). Panel members saw a demonstration of this system in the laboratory; it allowed the positioning of a needle tip with submicron accuracy and a range of tens of microns.

A brief review of work in the ETL was given by Dr. Kunikatsu Takase. Much of this work was aimed at merged robotic systems, where many small robots perform cooperative tasks to accomplish a larger effort. Specific topics included the development of technology for autonomous robot control, interactive man-machine interfaces, and distributed sensing systems, as well as the study of learning aspects of such systems (robot training and robots teaching robots). While robots are currently relatively large, the eventual devices are aimed at sizes comparable to a business card. The comment was made that if the devices were made much smaller than this, they would not be able to accomplish most real-world tasks, although for medical applications some structures would of course be still smaller. The applications in mind for much of this work appeared to be monitoring and small parts handling. There were also efforts on small micromachines. Stacked solid-state structures with 1 μm orifices containing electron emitters and grid overlays were shown with the intent of using these devices as end effectors for directed electron-discharge machining.

Dr. Yoshihisa Tanimura did not specifically describe the research activities in NRLM but laboratory representatives suggested discussing areas of mutual interest. There was considerable subsequent discussion of needs in MEMS and micromechanics. The laboratory representatives are interested in LIGA for applications in micromechanics, but felt that friction and microassembly of microcomponents were significant challenges. They felt that practical products with MEMS and micromachines are probably at least ten years out and did not seem very concerned about products within the next five years. They noted that their work was primarily focused on microactuators, which is primarily where the risks are: While useful sensors can certainly be realized, actuators are much less certain, and even though there are many possible drive mechanisms, they do not necessarily produce the desired effects and may be difficult to integrate. The researchers have a program in microinjection molding and are exploring its use in piezoelectric ceramic materials. On the subject of LIGA, they expressed concerns that this area was restricted by German patents and by additional work at Wisconsin in the United States. There was considerable discussion on this topic.

Panel members saw two projects in subsequent laboratory tours. The first involved work by Dr. Tatsuo Arai and others on the development of a dexterous micromanipulation system for use in microsurgery and microassembly. This was the piezoelectrically-driven structure mentioned above. Panel members first saw two macro versions of the system. The larger was several feet across and was aimed at construction applications (excavations). The smaller table-top device used feedback to accomplish tasks such as the insertion of a square peg in a square hole with very tight clearances. The microversion of this device used an end effector a few centimeters on a side positioning the tip of a needle a few centimeters long. They had not yet used the system for microassembly, but the overall feedback control was very nice and performed well.

The second project involved the use of ion implantation to modify materials. Specifically, the researchers used ion implantation to modify the elasticity of materials. They implanted 18 μm diameter wire to a depth of about 2 μm and studied its material properties. The shifts in Young's modulus were detectable; the effects on built-in stress and strain remain to be studied. The idea is to be able to use ion implantation to selectively tailor certain portions of a microstructure to produce flexible joints, where the structure itself was perhaps 2 μm thick. They showed one diagram of a silicon structure where ion implantation had been used with subsequent etching to give a void under an overhanging beam. The laboratory facilities were adequate for working with discrete hardware and advanced control systems. The JTEC panel did not see clean room facilities or any actual MEMS microfabrication.

QUESTIONNAIRE

The following questions were submitted to MEL and ETL prior to the panel's visit.

A. Advanced Materials and Process Technology

1. What materials and fabrication techniques are most likely to be used in production for MEMS? Will MEMS continue to be based primarily on silicon IC technology?

At present, Si-based technology plays a most important role in MEMS, but its role will decrease in the future. Expansion of available materials and process technology is [an] essential trend in MEMS or rather micromachine technology. We define "MEMS" as electromechanical systems fabricated by Si-based IC technology, and "micromachine" as [a] machine composed of microfunctional elements fabricated [with] various materials and process technology, which can do more complicated and precise work than conventional machines, for its more integrated structure.

2. What, in your opinion, is the most important new process or material needed for extending the capabilities of MEMS?

At this stage, this question is difficult to answer. In our project, the preceding four years' efforts will be focused on this issue. High-aspect-ratio fabrication processes, including etching and forming, seem important.

3. Are there plans to use X-ray lithography for micromechanics?

Yes.

4. How attractive is the LIGA process for commercial use in MEMS at the present time? How attractive do you expect it to be in five years? Ten years?

Reported products by LIGA are not always considered to be fabricated by only LIGA, and to make matters worse, patent issues and secret guarantees are a hindrance to our access.

5. If you are pursuing LIGA and LIGA-like high-aspect-ratio structures, what materials are being investigated and why? To what extent do you feel that structures produced using high-aspect etching will be competitive with those formed by plating?

Piezoelectric ceramics microstructure for ultrasonic application [are under investigation]. The latter question is not clear enough to be answered.

6. What are the prospects for a low-temperature wafer-scale bonding process for MEMS? How low in temperature can we go? Do you feel metal-metal, silicon-glass, or other interfaces are most promising?

Surface-activated bonding and Si surface modified bonding are candidates for low-temperature bonding. Interfacing of Si/metal and Si/ceramic are attractive for application.

7. To what extent will silicon fusion play a role in MEMS? Is the area coverage sufficiently high? How much of a real problem is the high bonding temperature?

Si fusion bonding is applicable to Si/Si bonding and SOI. The polishing and thinning processes after bonding are important. The process temperature is so high that its application is limited and difficult for bonding of dissimilar materials.

8. What polymeric materials are being explored as photomasks for high-aspect-ratio structures? Is the use of conformal coating processes practical?

These items are not direct targets of R&D of this project.

9. Polymers for thick photoresist applications are required by MEMS. Are Japanese photoresist suppliers responsive to this need?

Such resist [applications are] necessary, but IC industry also needs [them]. It seems to be better to wait for the development of IC.

10. Do you feel that nested/stacked wafer-level microstructures based on multiple bonding and/or etch-back operations will be feasible within the next five years? Are they important for MEMS?

They are very important to MEMS. The simplest one is expected to be feasible in five years.

11. It appears that precision injection molding could play a major role in MEMS. Would you comment on this, please.

This is already established for polymers. Application on metals and ceramics has high priority in R&D.

12. Are room-temperature superconductors being explored, and if so, what materials and processing techniques are being used?

In another project, superconductivity is [being] investigated, [so] there would be no necessity for R&D.

13. Do you expect major advances in micromachining curing the coming decade? Will photo-assist etching or new etch-stops emerge to play a major role? What other technology additions do you consider promising?

More precise and higher rates are expected for RIE; laser-assisted chemical etching is also expected.

14. What are the most important attributes you would insist on for a MEMS processing tool?

We must eliminate exclusiveness (dust impurities, etc.) of MEMS tools. Expansion of treatable material and flexibility of the tool must be pursued.

B. Sensors and Sensing Microstructures

1. For which sensed variables and types of sensors will MEMS technology have the greatest importance? What are the key advantages of MEMS technology for these sensors?

Medical use (chemical sensor), industrial use (gas sensor, acceleration sensor, gyro sensor), ultrasonic sensor, microforce sensor. Compact, lightweight, disposable.

2. Approximately when will the new sensors under development today based on MEMS technology first appear in the market place?

Various kinds of chemical sensors and ultrasonic sensors.

3. How can MEMS technology be used to improve existing sensors? What sensor types are likely to be improved the most?

Reducing size and weight, distributed intelligent. Pressure and tactile sensors may be refined.

4. What new sensors can only be developed using MEMS technology? How does MEMS make these new sensors feasible?

Two-dimensional array sensor, intelligent sensor, etc.

5. To what degree is self-testing likely to be possible with sensors? Will this be a major role for MEMS technology?

The problem of self-testing rather belongs to the problem of circuit-diagnosis than that of MEMS.

6. After pressure sensors and accelerometers, what is the next major sensor based on MEMS that will be mass-produced in high volume?

Medical use chemical sensors

7. To what degree are feedback readout schemes likely to be important in sensors? Will these feedback schemes involve MEMS?

We cannot understand the meaning of feedback readout schemes and this question.

8. What are the principal problems in the use of scanning surface probes (e.g. tunneling current) as an approach to high-sensitivity sensor readout? Is this approach likely to find wide application?

Making probes acute.

C. Microactuators and Actuation Mechanisms

1. Can designs using arrays of microactuators achieve large and useful forces? Are there other devices similar to the large optical projection displays that have been reported that can be realized using MEMS technology?

Arrays of microactuators can generate [large amounts of] power and are hopeful.

2. Considering their importance to MEMS, in what order of importance would you place the following microactuation mechanisms: shape-memory alloys, electromagnetics, electrostatics, thermal bimorphs, piezoelectric bimorphs, piezoelectrics, electrostriction devices, [and] phase-change devices? How many of these do you expect will find commercial applications in high-volume products?

We are going to study and develop all the microactuation mechanisms [that] are mentioned in the question. It is difficult to order the importance since the extent of importance [is] different for the application.

SMA, piezoelectric, and electromagnetic are hopeful in commercial use.

3. What are the most reasonable candidates for prime movers for microactuation?

The electrostatic force and electromagnetic force.

4. To what extent can sticking problems due to surface forces be suppressed in microactuators? Will these problems seriously constrain the practical application of microactuators based on narrow gaps?

So far, sticking is not a very serious problem, except for [the] rotational actuator. The dust problem is much more important.

5. What is the most promising candidate for a microrelay? Where are such devices most likely to be used?

The meaning of the first question cannot be understood. One of the answers is thought to be high current signal processing.

6. What are the main design issues in microfluidic systems? Where will such systems find their primary application?

The transport problem in capillary. The design method considering viscosity.

The blood-collecting equipments.

7. What designs are most likely to be adopted for practical microvalves and micropumps? What is holding up the practical realization of these devices?

The phase transformation excited by laser.

The miniaturization is difficult because of actuator size.

D. Sensor-Circuit Integration and System Partitioning

1. Will MEMS technology lead to complete microminiature "instruments on a chip?" For what types of instruments?

It is difficult for the present. An instrument only having sensing function may be possible.

2. Will MEMS technology combine sensors and actuators into complete control systems? If so, what types of control systems will be most affected?

Of course, MEMS technology combine sensors and actuators into complete control system. We cannot understand [the] latter question.

3. Are systems involving sensors, actuators, and embedded microcontrollers likely to be realized in monolithic form or will they be hybrid? What factors are driving for monolithic integration for what types of products?

We think [the] system will be used hybrid form. But if it is possible to make consuming power small and actuator by only silicon process, the system will be used monolithic form.

4. What levels of integration (transistor count) are we likely to see on MEMS chips by 1995? By the year 2000? Are full microprocessors needed or realistic?

The level of integration of MEMS does not correspond to that of IC.

5. To what extent will embedded microcontrollers be used in (possibly hybrid) integrated sensing nodes -- high-end devices only, or will they eventually become pervasive in even low-end products?

It is necessary to integrate low-end products if [the] sensing system is complex.

6. What are the prospects for adopting sensor bus standards, at least in specific industries (automotive, process control, HVAC)? How important is the evolution of such standards to the development of MEMS?

We presuppose that adopting sensor bus standards will be demanded primarily in the automotive industry. To avoid confusion, it is necessary to adopt standards in early stage. But R&D and the adapting standards should be parallel done.

7. Will sensor calibration continue to be done in hardware (laser-trimming or EPROM) or will it evolve to digital compensation in software? Is this an important issue in MEMS development?

It is better to do calibration in hardware, but [it] may be possible in software. For the present this problem has not yet been important in MEMS.

8. Will a few standard processes emerge to dominate sensor-actuator-circuit integration or will widely divergent processes continue to be the norm in MEMS? What issues will determine the answer to this question?

It is better that a few standard processes emerge. This is determined by designer's concept.

E. Advanced Packaging, Microassembly, and Testing Technology

1. What are the general directions for progress in packaging MEMS? What are the principal challenges here?

Packageless technique is anticipated.

2. What will be the application and impact of MEMS on the packaging of sensors?

The question is not specified to be answered.

3. How much of a problem is die separation for surface micromachined devices? Is this optimally performed after release?

At the moment, the problem has not yet been serious.

4. How important are the chip-level packaging schemes now under development to MEMS devices and systems? Is the increased process complexity worth it?

Chip level packaging is not so important in R&D, because the effort is early at this basic stage. For increasing complexity, it is not worthy commercially.

5. Are common packaging approaches across many types of devices feasible or will packaging continue to be very application specific?

Basically packaging is thought to be [a] versatile technology.

6. What viable techniques exist for coupling force from integrated microactuators while protecting the device from hostile environments? Can mechanical microactuators only be used inside hermetic packages?

Sealing and force transmission. There would be some mechanical actuators without [the necessity of] packaging.

7. To what degree should MEMS continue to focus on monolithic silicon microstructures and to what degree do you think it is really better suited to milliscale integration with components combined using microassembly techniques?

Sensing devices can be fabricated into monolithic [silicon microstructures], but the system with advanced functions must be fabricated by microassembly.

8. Are there microassembly techniques that can be sufficiently automated to make millielectromechanical devices in high volume at moderate or low cost? What are the generic barriers to such devices and techniques?

Automation is possible, in principle, but [is] commercially difficult for production diversity.

9. What techniques are available for testing MEMS structures after encapsulation/packaging? What happens when they are no longer viewable?

The system must be handled as a black box; viewability is favorable in [the] R&D stage.

F. MEMS Design Techniques, Applications, and Infrastructure

1. The term "MEMS" has many meanings. Could you tell us your interpretation?

We think that MEMS means microelectromechanical systems manufactured by IC processing technology and mainly made of Si.

2. Is there a MEMS technology driver equivalent to the DRAM in the IC industry? If so, what is it?

An integrated sensing and actuating device for automobiles, process controls and so on.

3. Is the integrated-circuit industry the principal application driver for MEMS? If so, what are the alternative drivers during the next decade, if any?

The integrated-circuit industry cannot be recognized [as] the principal application driver for MEMS, though it has seeds for MEMS. In the near future, the principal application drivers [will be] the automobile and medical industries.

4. In what sensor application areas do you see MEMS technology having the greatest importance? (Examples might be: automotive, medical, robotics, consumer products, etc.) What are the key advantages of MEMS technology for these applications?

[MEMS technology will be important in the areas of] automobiles, medical instruments, process controllers, etc. The advantages of MEMS are that they have small size, intelligence, disposability, low cost, etc.

5. What will be the application and impact of MEMS on the interfacing of sensors to the environment?

Since MEMS have small size, not only [can the] number of sensing points be increased, but also they can approach the target point.

6. Looking ahead five years, what new MEMS-based sensors and sensor applications do you anticipate?

Micromedical sensors.

7. In what time frame do you anticipate MEMS technology having the most impact on sensor products (for example, three years, five years, ten years, etc.).

Five years.

8. What is the prognosis for MEMS foundries? Are they needed? What technologies would need to be present in a MEMS foundry?

What are "MEMS foundries?"

9. What is the state of the art in MEMS reliability? Where are the principal problems?

Now MEMS are on the R&D, so they probably have poor reliability. The R&D of estimation technology is important.

10. What is the "state of the art" in MEMS designability? How important are CAD tools for MEMS? Do you have an active CAD effort for MEMS in your organization?

There is a CAD system developed by modifying a CAD system for IC design and IC process simulator, but there is not a CAD system for micromechanism or microstructure. MEMS CAD is not investigated, but [the] design concept of micromechanism is studied.

11. What priority would you place on the creation of a central MEMS database of material and design parameters? Does your organization have an active project in this area?

We place high priority on the creation of a MEMS database, but we do not have enough researchers to execute any active project.

12. How much funding is being directed into MEMS research and development in your organization? What percentage is this amount of the total R&D budget?

Unknown.

13. In your view, is enough funding available to support MEMS research in Japan? In the world? Are the principal bottlenecks to more rapid progress money or ideas?

In Japan, [MEMS R&D] should be funded three times as much as it is now. In the USA, [many] more companies should execute [MEMS R&D]. Money occupies 70 percent of the principal bottlenecks to more rapid progress.

14. What portion of your R&D funding for MEMS comes from internal, government or other sources? Has increased government funding had a major impact in your organization?

Government funding has a major impact on the development of microactuators, because it has a high risk for companies. They develop microsensors from funds on hand because sensors can be commercialized in the near future.

15. What percentage of your research is directed toward specific products? Toward basic research?

In the first half of the national R&D project, funds for basic research occupy the [larger] part.

16. What emerging technologies do you see as having the largest influence on MEMS and why (i.e., LIGA, superconductors, submicron ICs, piezoelectrics, thin-film magnetics, etc.)?

LIGA and LIGA-like high-aspect-ratio processing.

17. What are the principal barriers to the success of MEMS?

Finding various applications in many fields (for example: DRAM for IC technology).

18. What do you believe to be the major competitive technology alternative to MEMS?

Molecular machines (nanomachines) and improvement of various manufacturing technology.

19. Are patents a key to commercial success or are base technology skills more critical?

There are both species of patent.

20. The first generation of university graduates who specialized in MEMS are now finishing their degrees. Are employment opportunities for these students plentiful in Japan?

Because of [the] recession, employment opportunities are not plentiful for such students, but there are not enough researchers in this field.

REFERENCES

Arai, T., R. Larsonneur, and Y.M. Yaya. 1993. "Basic Motion of a Micro Hand Module." *Proc. 1993 JSME Int. Conf. on Adv. Mechatronics.* Pp. 92-97.

Arai, T., and R. Stoughton. 1992. "Micro Hand Module Using Parallel Link Mechanism." *Proc. Japan-USA Symposium on Flexible Automation.* ASME Book No. 10338A. Pp. 163-157.

Site:	**Micromachine Center (MMC)** **3F Sanko Building** **3-12-16 Mita, Minatoku** **Tokyo 108, Japan**
Date Visited:	September 27, 1993
Report Author:	L. Salmon

ATTENDEES

JTEC:

J. Giachino
H. Guckel
B. Hocker
G. Holdridge
S. Jacobsen
R. Muller
L. Salmon
C. Uyehara
K. Wise

HOSTS:

Takayuki Hirano	Executive Director, Host
Takayuki Tsunemi	Managing Director, Chief of Secretariat
Akira Inoue	General Manager
Makato Takahashi	Counselor
Takaharu Idogaki	Manager, Research Department

NOTES

The visit began with an overview of the center, including background information about the Micromachine Center. The Micromachine Center was founded in January 1992 to promote micromachine technologies, including coordination of the research and development portion of the MITI Micromachine Technology Project. The project funds are given by MITI to NEDO which, in turn, awards the funds to the Micromachine Center, which then writes contracts to individual companies. The objectives of the center are to: (1) establish micromachine technology; (2) disseminate the technology to industry; (3) help industry develop commercial applications with the technology; and (4) foster international collaboration in the area of micromachine technology.

There are four types of membership: "Research Supporting," "Group Supporting," "General Supporting," and "Special Supporting." Current membership is shown in Table Micro.1. The research supporting membership consists of Japanese companies that are funded directly by MMC to perform research for the MITI micromachine program. The group supporting membership consists of two Japanese industrial associations that are interested in the research performed by the center and the four non-Japanese institutions are included in this list since one is a company, one is a non-profit organization, one is a government laboratory, and the fourth is a university.

Table Micro.1
MMC Membership

Research Supporting Members	**Group Supporting Members**
Aisin Cosmos R&D Co., Ltd.	Japan Industrial Robot Association
Fanuc Ltd.	Japan Power Engineering and Inspection Corporation
Fujii Electric Corporate Research & Development, Ltd.	IS Robotics, Inc. (U.S.A.)
Fujikura Ltd.	SRI International (U.S.A.)
Hitachi, Ltd.	Royal Melbourne Institute of Technology (Australia)
Kawasaki Heavy Industries, Ltd.	Kernforschungszentrum Karlsruhe GmbH (Germany)
Matsushita Research Institute Tokyo, Inc.	
Meitec Corporation	
Mitsubishi Cable Industries, Ltd.	
Mitsubishi Electric Corporation	**General Supporting Members**
Mitsubishi Heavy Industries, Ltd.	
Mitsubishi Materials Corporation	Komatsu Ltd.
Murata Manufacturing Co., Ltd.	Sony Corporation
Nippondenso Co., Ltd.	Sumitomo Corporation
Olympus Optical Co., Ltd.	Ford Motor Company Ltd.
Omron Corporation	
Sanyo Electric Co., Ltd.	
Seiko Instruments Inc.	**Special Supporting Members**
Sumitomo Electric Industries, Ltd.	
Terumo Corporation	The Dai-Ichi Kangyo Bank, Limited
Toshiba Corporation	The Daiwa Bank, Limited
Yaskawa Electric Corporation	
Yokogawa Electric Corporation	

The general supporting membership consists of companies that have access to all information developed through the center, but do not have any intellectual property rights to the work developed with NEDO funds. Membership in this category is open and new members can be added at any time. Membership in the research category is closed because all members in the research category are participating in the ongoing MITI project. Group supporting membership consists of organizations such as non-profit enterprises. The fourth type of membership, special supporting members, now consists of the banking institutions that handle funds of the center. The fees paid by the members become discretionary funds for MMC. Research supporting members also provide staff on assignment to manage the R&D program of the center.

The staff members of the micromachine project see micromachine technology as a common component of solutions to three major industrial challenges. The first challenge mentioned was that of increasing the efficiency of large, complex industrial facilities by improving the reliability of such facilities and by reducing the cost required to maintain them. The power plant pipe maintenance project in the MITI program is an example of how micromachines can help address the challenges faced by such facilities.

The second challenge mentioned was that of decreasing the environmental impact of industrial production systems. Micromachines can help achieve goals in this area by reducing energy consumption of industrial production, and by reducing consumption of natural resources.

The third challenge is the reduction of trauma to the patient during medical procedures. Micromachines can assist in this area by providing alternatives to surgery and by reducing trauma caused during necessary surgery. Micromachines can also assist in the diagnosis of medical conditions.

The MITI micromachine program focuses on a micromachine system for pipe maintenance/repair in a power plant. The project is divided into four parts that correspond to the four micromachines that comprise the projected system: the central control and distribution module (mother ship); the floating observation vehicle (microcapsule); the wireless, directed repair and observation module (inspection module); and the wired, directed repair and observation module (operation module). Each part of the project was given to a team of companies with one company chosen as the head of the team. The purpose of the project is not to produce the projected system as a product, but rather to develop the technology that will enable such a project to be built.

The first five years of the project are designed to investigate the research requirements of the project. During this phase changes can be proposed to MITI for approval. After the first five years, the project will be evaluated by NEDO and

MITI. An evaluation team will consist of representatives from universities, industry (both producers and suppliers), and government. AIST will evaluate not only the technical progress of the program, but also the effectiveness of the project in attaining national goals, a process that AIST appears to be pioneering with this project. The center is staffed by assignees from industry (currently three) and national laboratories (currently one). They serve for a term of two years and then return to their institutions.

Two tables were shown that summarize the connections between the different parts of the MITI micromachine effort. Table Micro.2 is a matrix of the parts of the overall project and the major system component technologies required to build the system. For example, an energy supply is required for all four parts of the system, but each module requires a different type. The project will result in research directed toward at least four different types of energy sources. Since the purpose of the project is to develop technologies, research in energy supplies with different characteristics is desirable.

Table Micro.3 shows a matrix of micromachine modules and the fabrication technologies required to build the module. For example, a complementary set of dry processes will be developed by a module team. The result will be a broad range of fabrication approaches.

The matrix approach illustrated by these tables is indicative of an effort to develop parallel approaches to difficult technological and fabrication challenges. Pursuit of parallel approaches is consistent with the goals of the program, to develop the best fundamental micromachining technology possible for future applications that are not limited to power plant maintenance and repair.

In addition to the national project, the center also administers an independent R&D program using the funds provided by the companies. The center's purpose is to coordinate research in the micromachine area, specifically for the national project. The center also is looking into the area of supporting university research.

Table Micro.2
Elemental Technology Map

	Micro Capsule	Mother Ship	Inspection Module (without wire)	Operation Module (with wire)
Energy Supply	Micro dynamo	Micro battery (Hydrogen absorption alloy)	Microwave transmission Photo-electric convertion (solar battery type)	Photo-electric conversion (p-n junction type)
Actuator Mechanism	Electromagnetic motor for steering Speed increaser	Pneumatic clamping Electrostatic driving mechanism	Inching worm driving mechanism Piezoelectric motion drive Functional connection	SMA manipulator Photo stimulated operation Gear train Locomotion High power source
Sensor	Ultrasonic detection Micro gyroscope	Photo-scanning device	Ultrasonic micro sonar Micro visual sensor Micro photo spectroscopy	Environment recognition by image fiber
Communi-cation	Signal transmittion by piezo composite		Communication network	
Control	Dynamical motion control	Behavior control Group control	Teleoperation Coordination control	Multi-joint-manipulator control

Table Micro.3
Fabrication Technology Map

	Micro Capsule	Mother Machine	Wireless Inspection Module	Wired Operation Module
Dry process	Multi-source sputtering Laser-assisted etching RIE, FIB	Reactive sputtering Photo-assisted CVD Plasma ion plating ECR etching	Ion plating, FIB Localized plasma laser fabrication Laser-assisted etching	3 dimensional dry etching Plasma dry etching
Bonding Mounting	Surface activation bonding	Packaging	Room temp. bonding 3 dimensional mounting Packaging	Multilayer bonding Anodic bonding Laser micro welding
EDM	5 degrees of freedom NC EDM/ECM	High precision 5 DOF EDM	Micro die sinking EDM	
Assembling	Micro manipulator	Micro manipulator	Micro manipulator	Micro manipulator
Other process	LIGA Ceramic injection molding			Metal injection molding Photo enhanced electrolytic 3 dimensional process

Site: **Mitsubishi Electric Corporation**
8-1-1 Tsukaguchi Honmachi
Amagasaki
Hyogo 661, Japan

Date Visited: September 30, 1993

Report Author: J. Giachino

ATTENDEES

JTEC:

J. Giachino
R. Muller
C. Uyehara

HOSTS:

Dr. Hideharu Tanaka	Deputy Manager, Advanced Mechanical Systems Department
Dr. Ken Morinushi	Manager, Advanced Mechanical Systems, 5th Group Department
Minoru Kobayashi	Research Manager
Takuji Oda	Research Engineer, Materials Processing Engineering Department

BACKGROUND

Mitsubishi Electric Company has 102,704 employees and annual sales of $25.7 billion. There are four laboratories:

- o Central Research
- o Manufacturing Development
- o Materials and Electronic Devices
- o Industrial Electronics and Systems

The MEMS work has approximately twenty researchers involved and is funded at the level of ¥2 to ¥3 billion per year.

Following are some of the areas that these laboratories are working in:

- o Central Research
  - Advanced and new technologies
  - Optical neural computer
  - X-ray lithography
  - Atomic layer
  - Phosphoric fuel cell
  - Stirling Engine
  - Ozone generator

- o Manufacturing Development
  - Technology
  - High-precision prototypes
  - TAB
  - Fine-pitch soldering
  - Thin films

- o Materials and Electronics Devices
  - New materials
  - Analysis and evaluation support
  - High-temperature superconductors
  - LCD using TFT
  - Simulation

- o Industrial Electronics and Systems
  - Optical discs
  - Power electronics
  - Advanced factory automation
  - Electrical discharge with fuzzy logic
  - Automotive electronics

The JTEC panel saw a video that included pictures of a synchrotron X-ray source and extensive automated packaging and assembly equipment.

QUESTIONNAIRE

Following are the Mitsubishi responses to a series of questions submitted before the JTEC panel's visit. Only those questions for which a response was given have been included.

A. Advanced Materials and Process Technology

1. What materials and fabrication techniques are most likely to be used in production for MEMS? Will MEMS continue to be based primarily on silicon technology?

Magnetic layers and structures is the key to MEMS. [These factors are] more important than electrostatic. Silicon is just one technology. Silicon suffers from the fact that it is basically a two-dimensional technology, and for MEMS one needs a three-dimensional technology.

2. What, in your opinion, is the most important new process or material needed for extending the capabilities of MEMS?

Three-dimensional capability and high aspect ratio. Thick film-type materials are also important, as well as the capability of measuring the internal stresses in these thicker materials. These materials need to have improved conducting, insulating, and magnetic properties.

Questions 3, 4, and 5 are all answered in one response:

3. Are there plans to use X-ray lithography for micromechanics?

4. How attractive is the LIGA process for commercial use in MEMS at the present time? How attractive do you expect it to be in five years? Ten years?

5. If you are pursuing LIGA and LIGA-like high-aspect-ratio structures, what materials are being investigated and why? To what extent do you feel that structures produced using high-aspect etching will be competitive with those formed by plating?

[Mitsubishi is] getting a synchrotron ring internally. There is one already available in the area for use. Compared to IC industry, MEMS volumes are low so that there is a need to develop low-cost equipment and low-learning costs. The [corporation is] looking for new processes for plating and fabrication.

6. What are the prospects for a low-temperature wafer-scale bonding process for MEMS? How low in temperature can we go? Do you feel metal-metal, silicon-glass, or other interfaces are most promising?

[Mitsubishi is] doing atomic bonding at room temperature. This requires very clean surfaces (sputter etch) and ultralow vacuum 10 exp-10 Torr. The [company has] done Si/Ag and Si/Si bonds with no pressure at room temperature.

7. What polymeric materials are being explored as photomasks for high-aspect-ratio structures? Is the use of conformal coating processes practical?

[The company uses] material from Hoechst in 20 to 30 micron layers per application. This requires three coats to get to 100 microns. This is not very practical. [The company is] trying to develop a new material.

8. Do you feel that nested/stacked wafer-level microstructures based on multiple bonding and/or etch-back operations will be feasible within the next five years? Are they important for MEMS?

Silicon is not [the company's] main technology for MEMS. This has been done in the semiconductor group.

9. It appears that precision injection molding could play a major role in MEMS. Would you comment on this, please.

Plastics are useful in the millimeter size. In the micron size it is difficult [since] viscosity becomes a problem for cavity injection of the polymer.

10. Are room-temperature superconductors being explored, and if so, what materials and processing techniques are being used?

[Mitsubishi has] developed a Bi/Sr/W/CuO superconductor by sputtering. [This] application is not available for discussion.

11. Do you expect major advances in micromachining in the coming decade? Will photo-assist etching or new etch-stops emerge to play a major role? What other technology additions do you consider promising?

[The company is] working on a new technology and [has] substantial funding to pursue it.

C. Microactuators and Actuation Mechanisms

1. Can designs using arrays of microactuators achieve large and useful forces? Are there other devices similar to the large optical projection displays that have been reported that can be realized using MEMS technology?

There is a need to do arrays in order to realize a useful device. [The company has] been working on sensor and actuator arrays, [and believes] that in five years a sensor array will be in a product. MEMS displays will be a product for an actuator array. Sony [already] has an actuator display.

2. Considering their importance to MEMS, in what order of importance would you place the following microactuation mechanisms: shape-memory alloys, electromagnetics, electrostatics, thermal bimorphs, piezoelectric bimorphs, piezoelectrics, electrostriction devices, and phase-change devices? How many of these do you expect will find commercial applications in high-volume products?

Electromagnetism for high power density, piezoelectric for large force, electrostatic for simplicity.

3. What are the most reasonable candidates for prime movers for microactuation?

Electromagnetism.

4. To what extent can sticking problems due to surface forces be suppressed in microactuators? Will these problems seriously constrain the practical application of microactuators based on narrow gaps?

[Mitsubishi] believes that one must [achieve] a noncontacting system. [The company is] working on an air bearing.

5. What is the most promising candidate for a microrelay? Where are such devices most likely to be used?

[Mitsubishi has] no interest in a microrelay.

6. What are the main design issues in microfluidic systems? Where will such systems find their primary application?

[The] main design issues are high viscosity and friction reduction. The primary applications will be in cooling systems for VLSI.

7. What designs are most likely to be adopted for practical microvalves and micropumps? What is holding up the practical realization of these devices?

Piezoelectric valves are the most likely. For greater than 1 mm, rotary pumps will be used; for less than 1 mm, positive displacement pumps [will be used]. Friction and leakage problems are the major concerns.

F. MEMS Design Techniques, Application, and Infrastructure

1. The term "MEMS" has many meanings. Could you tell us your interpretation?

The key to be[ing] successful is to combine sensors and actuators in arrays. So "array" is probably the best definition. Machine has no meaning.

2. Is there a MEMS technology driver equivalent to the DRAM in the IC industry? If so, what is it?

Optical applications using arrays.

3. Is the integrated circuit industry the principal application driver for MEMS? If so, what are the alternative drivers during the next decade, if any?

[Mitsubishi does] not see silicon as a major driver. MEMS needs new ideas for applications.

4. In what sensor application areas do you see MEMS technology having the greatest importance? (Examples might be: automotive, medical, robotics, consumer products, etc.) What are the key advantages of MEMS technology for these applications?

Consumer products, robotics, medical, automotive.

5. Looking ahead five years, what new MEMS-based sensors and sensor applications do you anticipate?

Sensor arrays.

6. In what time frame do you anticipate MEMS technology having the most impact on sensor products (for example, three years, five years, ten years, etc.).

Three to five years.

7. What is the prognosis for MEMS foundries? Are they needed? What technologies would need to be present in a MEMS foundry?

[A MEMS foundry] would not be commercially viable.

8. What is the "state of the art" in MEMS reliability? Where are the principal problems?

The major concerns [are] erosion and environmental dirt.

9. What is the "state of the art" in MEMS designability? How important are CAD tools for MEMS? Do you have an active CAD effort for MEMS in your organization?

[The company needs] to develop tools to measure material properties. [Mitsubishi does] not yet have good material property data.

Site: **Nagoya University**
Department of Mechano-Informatics and Systems
Furo-cho, Chikusa-ku
Nagoya 464-01, Japan

Date Visited: October 1, 1993

Report Author: G.B. Hocker

ATTENDEES

JTEC:

J. Giachino
G.B. Hocker
R. Muller
C. Uyehara

HOSTS:

Kazuhiro Kosuge	Associate Professor
Fumihito Arai	Research Associate

RESEARCH AND DEVELOPMENT ACTIVITIES AND DISCUSSIONS

The JTEC panel's visit was to Professor Fukuda's group in the Laboratory of Robotics and Mechatronics in the Department of Mechano-Informatics and Systems in Nagoya University. The department has five research groups, each with a senior professor, an associate professor, and about two research associates. Professor Fukuda was travelling, so the panel was hosted by two other members of his research group, Professor Kazuhiro Kosuge and Dr. Fumihito Arai.

The basis for this group's research is large-scale robotics. The Nagoya area contains a variety of aerospace, machine, and robotics industries, and the laboratory has many collaborations with industry. This group's approach to microrobots is based on demonstrating and developing concepts on a large scale, then developing microrobotic versions. The group's general activities were reviewed, followed by a laboratory tour and a series of demonstrations. A video was presented describing the group's work on micromachines and mobile robots. This included: (1) a mobile robot for travel in pipes, based on giant magnetostrictive alloy actuators controlled by external magnetic fields (ultimately, the plan is to reduce the size of the robot for travel in blood vessels); (2) a multiple degree-of-freedom electrostatic actuator; (3) a photostrictive PLZT bimorph actuator controlled by UV light (a mobile robot based on this actuator was very slow due to friction, but moved more freely on an air table); (4) an underwater mobile robot propelled by a resonant piezoelectric actuator; and (5) a miniature walking robot propelled by a vibrating foot actuator. All of these devices represent only externally controlled propulsion schemes at this time, without built-in control or manipulation capability. All are in the size range of a few centimeters. A multiple degree-of-freedom catheter was demonstrated. This uses shape memory alloy actuators to flex the catheter for directional control, and was apparently first demonstrated at Olympus. The SMA material used has a transition temperature in the 40°C to 45°C range. The group is also working on a micropump for drug delivery. A small Class 1,000 clean room (about 5 x 5 meters) was shown.

A variety of large-scale robots were shown, including: (1) a self-organizing cellular robot (CEBOT) consisting of a variety of function cells that can be connected to suit a given task (its operation was demonstrated in a video); (2) cellular end effectors (manipulators for CEBOT arms, which can combine torque sensors, stereo TV, and optical sensor arrays on the arms); (3) a brachiation robot, using two arms to swing between overhead handholds (the arms include Murata piezogyros for angular position and rate information); and (4) image processing for plant cell classification and counting.

The visit concluded with discussions concerning MEMS and the panel's list of questions and issues. The major application area foreseen is medical, with automotive mentioned as another user. The researchers stated that force and tactile sensing are required, along with other sensors, for feedback control of robots. Calibration is a stated problem for many of these sensors; calibration in software is thought to be easier than in hardware. Also desired is wireless signal transmission to miniature robots. They are not sure if arrays of microactuators are practical, and are examining a wide variety of actuators, not all of which are microminiature. While the group is interested in silicon microfabrication and in LIGA, they expressed a strong need for true 3-D capabilities and so are looking at many alternative fabrication techniques. A desire was stated for 3-D CAD software, with a package apparently available from Seiko for ¥3,000,000.

REFERENCES

Proceedings of the Third International Symposium on Micro Machine and Human Science. 1992 October 14-16. Nagoya, Japan.

Research Activities, October 1989 - December 1992, Laboratory of Robotics and Mechatronics, Department of Mechano-Informatics and Systems, Nagoya University.

Site:	**Nippondenso Research Laboratories** **500-1 Minamiyama, Komenoki** **Nisshin-cho, Aichi-gun** **Aichi-ken 470-01, Japan**
Date Visited:	September 30, 1993
Report Author:	G.B. Hocker

ATTENDEES

JTEC:

J. Giachino
G.B. Hocker
R. Muller
C. Uyehara

HOSTS:

Dr. Tadashi Hattori	General Manager
Takashi Kurahashi	Project Manager
Dr. Nobuaki Kawahara	Researcher
Dr. Masao Nagakubo	Researcher
Kunihiko Sasaki	Researcher

RESEARCH AND DEVELOPMENT ACTIVITIES AND DISCUSSIONS

Nippondenso is a major manufacturer of automobile components worldwide -- number one in Japan and number three worldwide -- with sales of over $12 billion and recent income of $400 million. Nippondenso was founded in 1949, and is part of the Toyota group of companies. Nippondenso Research Laboratories were established in 1991 and employ 300 people, 170 of whom are researchers. Research fields include semiconductors, control systems, robotics, micromachines, artificial intelligence, and biomaterials. The seven-story laboratory building has much space available for expansion. The connected test center buildings have two Class 10 clean rooms.

The panel was greeted by Dr. Tadashi Hattori, the general manager. An introductory video tape showed Nippondenso's microcar activities. Dr. Nobuaki Kawahara led much of the discussion. About thirty people work on micromachining and about ten on their part of the national micromachine project.

Their first target for MEMS technology is sensors; the second target is for small optical devices where large forces and mass are not required. Major efforts have focused on an integrated pressure sensor for engine control, and on an integrated air bag crash sensor. The former is a piezoresistive diaphragm device 2.8 mm square. The latter is based on an etched cantilever with piezoresistors, 8.3 x 3.6 mm, and packaged in silicone oil for damping. Both use extensive on-chip circuitry. A clever Si diaphragm, variable focus mirror was shown. It is electrostatically deflected, and the properly shaped optical surface is obtained by varying the diaphragm thickness with complex micromachining according to a design reached by FEM analysis. Bar code readers, a Nippondenso product, were said to be the application.

An extensive laboratory tour also included demonstrations of the microcars in operation, a miniature microwave-powered plane, and thin film electroluminescent displays in orange-yellow, red, and green, planned for production in a few years. Posters described Si wafer bonding for sensors, power devices and ICs, and laser microetching of PZT in pure water with a Nd:YLF laser. Also demonstrated were an inchworm actuator based on electromagnet relays, and development of technology for bonding Si wafers to aluminum.

In subsequent discussions, Nippondenso researchers indicated that their primary interest is in micromachining technology developments. They are using bulk micromachining and trying to get surface poly-Si micromachining wafer bonding technology into production. They believe LIGA is very expensive, limited in the types of materials it can use, and cannot make truly 3-D surfaces. They are concentrating on piezoelectrics and electrostatics for miniature actuators, since these do not produce heat. Their work in the national (MITI) micromachine project is on sensors and actuators, concentrating on materials other than Si, such as piezoelectrics. They work with several university professors on sensors and actuators, wafer bonding, and amorphous Si, but do not send their researchers to the universities. An estimated typical time to market a new technology was: two years to develop a research prototype, four additional years to develop an engineering prototype, and four more years to introduce the final product in the marketplace.

REFERENCES

Creative Research Lab brochure (mostly in Japanese).

Nippondenso Corporate Guide.

Ohtsuka, Y., et al. "Three-dimensional Pattern Recognition by Range Finder with Laser Beam Sensor."

Saeki, K., et al. 1992. "Aberration Reduction of Si Diaphragm Dynamic Focusing Mirror." Paper presented at Third International Symposium on Micro Machine and Human Science. 14-16 October. Nagoya, Japan. (Also presented at MEMS '93).

Tesigahara, A., et al. 1992. "Fabrication of a Shell Body Microcar." Paper presented at Third International Symposium on Micro Machine and Human Science. 14-16 October. Nagoya, Japan. (Note that full proceedings were provided by University of Nagoya).

Site: **NTT Interdisciplinary Research Laboratories**
Nippon Telephone and Telegraph Corporation
3-9-11, Midori-Cho, Musashino-Shi
Tokyo 180, Japan

Date Visited: September 30, 1993

Report Author: L. Salmon

ATTENDEES

JTEC:

H. Guckel
S. Jacobsen
L. Salmon
K. Wise

HOSTS:

Dr. Hiroki Kuwano	Senior Research Engineer, Supervisor Sensing Systems Research Group, Optomechatronics Laboratory
Dr. Reizo Kaneko	Associate Vice President, NTT Director, Kaneko Research Laboratory
Renshi Sawada	Senior Research Engineer, Supervisor Optomechatronics Laboratory
Dr. Hiroshi Hosaka	Senior Research Engineer, Sensing Systems Research Group, Optomechatronics Laboratory

NOTES

Dr. Kuwano began by providing an overview of NTT and the Interdisciplinary Research Laboratories. He indicated that the downturn in the economy and NTT's current financial difficulties will not cause reduced research efforts at his laboratory because NTT views research as the mechanism to develop future opportunities for growth.

The Interdisciplinary Research Laboratories employs approximately 300 researchers and consists of three major laboratories: Mechaphotonics, Energy Electronics, and New Materials and Properties. The Energy Electronics Laboratory concentrates on development of new energy systems, and the New Materials and Properties Laboratory concentrates on the characterization and development of new materials. Dr. Kuwano is Manager of the Sensing Systems Research Group in the

Mechaphotonics Laboratory. The mission of the Mechaphotonics Laboratory is to use micromechanical technology to improve the density and performance of optical storage media, and to improve the assembly and alignment of optical fiber systems. There are approximately thirty researchers at NTT working on MEMS technology. NTT is not a participant in the MITI/AIST micromachine effort.

The NTT researchers indicated that they believe that planar lithographic-based fabrication is most appropriate for MEMS because of its potential for manufacturability. They also indicated that the NTT group is rare in Japan because it combines the talents of individuals with skills in the areas of microfabrication and mechanical engineering. They spend much of their efforts testing MEMS structures and measuring their properties.

During a discussion of the commercial applications of MEMS, the NTT researchers indicated that the major driver for MEMS technology is reduction in cost of completed systems. Another strength of MEMS that they plan to exploit is the possibility of integrating electronics with the mechanical system. Renshi Sawada estimated that it would take approximately five years to commercialize a product such as the optical encoder he is working on.

After the overview discussion, the JTEC panel toured the Kaneko Research Laboratory. Dr. Reizo Kaneko is the director of the laboratory and has a position analogous to that of an IBM Fellow. His laboratory concentrates on microtribology and micromotion in biology. Researchers in the laboratory are using STMs to study wear on surfaces by measuring the damage caused by motion on clean surfaces and on surfaces that have foreign species adsorbed on them. STM micrographs show the effect of wear at the atomic level, and indicate the sources of friction on an atomic scale. The laboratory is also studying method of locomotion in bacteria. Researchers are using STM micrographs of the physical structures responsible for bacteria locomotion in order to better understand the mechanics of that motion. The physical structures in bacteria are complicated, and it is difficult to determine the mechanics of their locomotion.

After the tour of the Kaneko Laboratory, the JTEC panel toured the Mechaphotonics Laboratory facilities. Mr. Sawada described a microoptical encoding head that was reported at the MEMS '91 meeting. The encoder is a monolithic integration of a multiple quantum well laser source, a split beam interferometer, a photodiode, and the lenses needed to focus the lasers on the surface of the optical media. Mr. Sawada indicated that the encoder can improve resolution to better than 10 nm. A schematic of the encoder is shown in Figure NTT.1. The laser used internal reflection at the edges of the laser to provide the two split laser beams. The laser light is then focused through two lenses made of graded SiON. The light is focused in three dimensions. It is focused in the plane of the wafer surface by the physical curvature of the lens, and in the direction perpendicular to the surface by the grading of the nitrogen concentration of the sputter-deposited SiON film. The encoder head structure can accurately measure the distance to the optical media because the optical media forms one side of the laser cavity. If the encoder to disc distance is not correct, laser output will be sharply reduced.

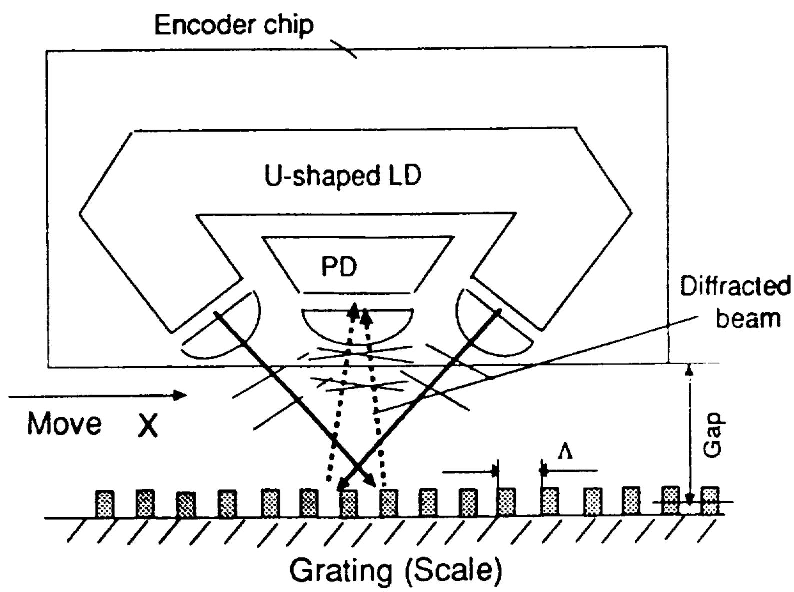


Figure NTT.1. Schematic of the monolithic optical encoder.

The JTEC panel also saw a project that uses micromechanical structures to align optical fibers during assembly. Figure NTT.2 illustrates the basic concept used. Metal is deposited on the side walls of a "V" groove etched in a substrate; the end of the optical fiber is also metalized. When a bias is applied between the metalized fiber and the electrodes on the groove, the end of the fiber can be moved to the left or the right. Optical power output can be utilized as a feedback source to the electrode bias in order to optimize optical coupling between the fiber and the next optical channel. The structure is sufficiently robust to withstand shorting of the fiber to the electrode. Unfortunately, this method cannot be used to keep the fiber fixed during cure of the epoxy used to cement the fiber in place, but optical losses caused by movement during the cure are relatively small.

The NTT researchers also described use of a flat spring structure as a relay and as a microvalve actuator. A schematic of the flat spring, which is made from permalloy on silicon, is shown in Figure NTT.3. Actuation is currently made through application of an external magnetic field produced by coil. Future work will attempt to fabricate integrated electromagnets for actuation. The spring is made of 2 micron thick permalloy (Ni 80%/Fe 20%) and is deposited using sputtering.

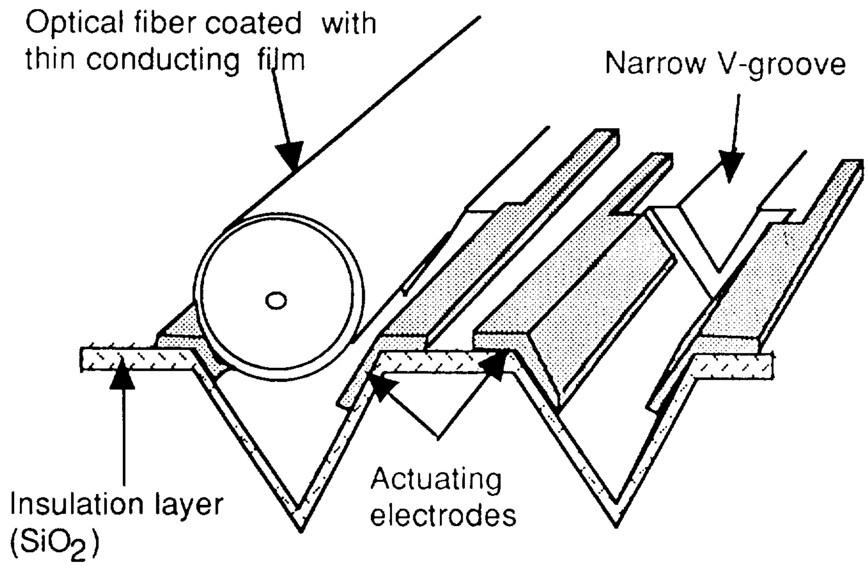


Figure NTT.2. Schematic of the fiber alignment approach.

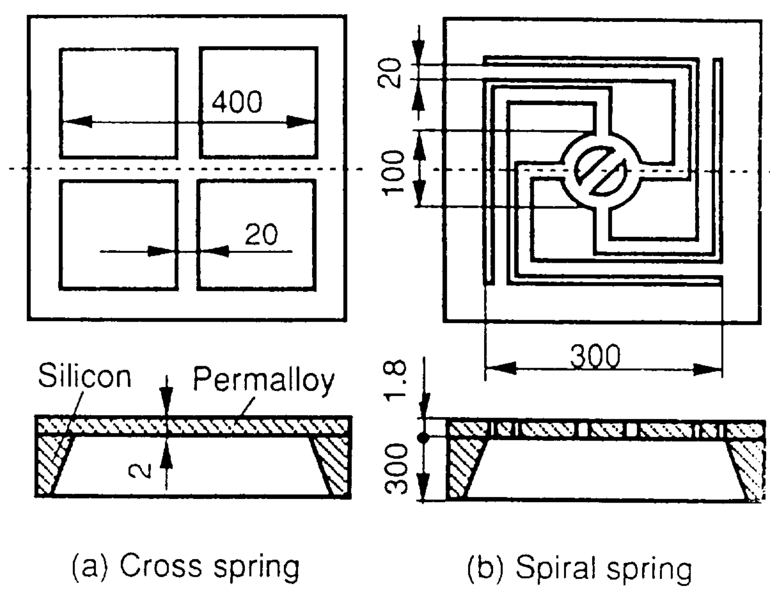


Figure NTT.3. Schematic of the flat spring actuator.

For use as a relay, movement of the flat spring closes or opens a relay contact. The relay can withstand up to 400 V, has a contact force of approximately 10 mg, and has a response time of less than 1 ms. The staff at the Interdisciplinary Research Laboratories see this relay fulfilling an important function as a relay for the high voltage signals in telephone terminal switches.

The flat spring can also be used as an actuator for a microvalve as shown in Figure 6.16 (p. 95). The throat of the valve is 30 microns in diameter, and the valve has a leak rate of 1.5×10^{-5} Torr liters/second, and a standing pressure of greater than one atmosphere.

Site:	**Olympus Optical Co., Ltd.** **2-3 Kuboyama-cho** **Hachioji-shi** **Tokyo 192, Japan**
Date Visited:	September 29, 1993
Report Author:	R.S. Muller

ATTENDEES

JTEC:

S. Jacobsen
R.S. Muller
C. Uyehara

HOSTS:

Yasutake Hirachi	General Manager
Kazuhisa Yanagisawa	Assistant General Manager
Atsushi Yusa	Director, Semiconductor Technology Center
Shu-Ichi Takayama	Manager, Endoscope Division

BACKGROUND

Dr. Atsushi Yusa, Director, Semiconductor Technology Center, gave an overview to the JTEC panel. Olympus Optical Company, founded in 1919, employs 5,300 people. Sales were ¥185.7 billion in 1992, although this figure decreased in 1993. Products and the company's percentage of total business in 1992 were: endoscopes 45.3 percent; cameras, 30.7 percent; clinical devices, 4.5 percent; and the remainder in smaller categories. Research and development expenditures were ¥24.5 billion. The basic expertise areas at Olympus can be divided into: optical engineering, medical engineering, production engineering, semiconductor devices, microoptics, advanced materials, and micromachines.

The endoscope business at Olympus is forty years old, but endoscopes only became the dominant business about fifteen years ago.

Olympus showed the JTEC panel a video describing the uses of endoscopes and presenting ideas for their further development, including removal of polyps and kidney stones; laser cutting; and electric-spark breakdown of kidney stones. The video showed a 12 mm (OD) ultrasound source (rotatable) with scanner and sensor, with rotation achieved using the principle of a speedometer cable.

RESEARCH AND DEVELOPMENT ACTIVITIES

The company showed the panel a research project for building a snake endoscope and a 2.6 mm (OD) SMA catheter containing an 0.8 mm periscope. The total length of the SMA catheter was ~2 m. Its intended use is for bile-duct investigation. The snake actuation is by segmented shape-memory-alloy elements that are activated by heating. Power and internal heating are problem areas. Other SMA problems include response time and hysteresis actuation by other means. Liquid pressure may provide an alternative to SMA.

Another project is an atomic-force microscope (AFM) using a microfabricated silicon-processed tip made from low-stress silicon nitride in a process learned from work at Stanford University. Olympus reported this project at the 1991 MEMS conference at NARA. Olympus has contracted with Stanford and sent an engineer to acquire this technology by working for two weeks with Professor Quate and researcher Akamine. A new angled tip developed at Olympus is shown in Figure Olympus.1.

SUMMARY

The discussion focused on MEMS challenges in the endoscope field. Olympus' view is that high-aspect ratio and larger parts are needed for their work. LIGA, while interesting, is not likely to be of value to them because of the cost and uncertain understanding of LIGA-deposited materials.

Olympus feels that other high-aspect-ratio techniques can and will be applied, such as:

- Magnetically controlled reactive-ion etching (RIE, shown by NTT at Transducers '93) and/or
- Oxygen-plasma RIE, as shown in polyimide by Tohoku University researchers at Transducers '93 (Esashi). Olympus has an engineer working on this at Tohoku.
- The company's view of the Nanohana project, a LIGA-type foundry, is that it is still in a very early stage -- too early for discussion.

- Olympus is team leader for the medical area of the MITI program (with Omron and Terumo), but the budget from AIST is small at present.

- Olympus has a focus that will center on nonsilicon processes because of the company's special needs.

  This focus is fairly well shared by other MITI-project companies. A company representative said that "many companies are in silicon technology; therefore it is not desirable to focus the new MITI program on this."

- Olympus also said that the United States and Europe are currently leading Japan in Si-based MEMS.

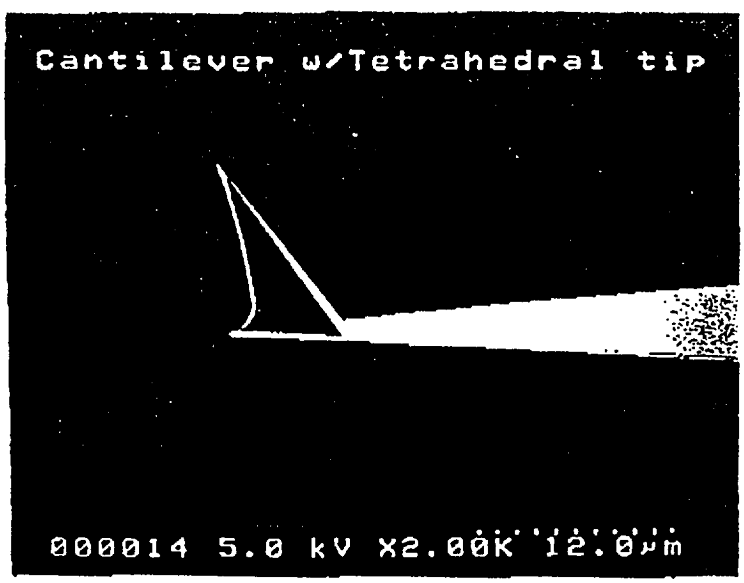


Figure Olympus.1. New angled tip developed at Olympus.

Site: **Omron Corporation**
Central R&D Laboratory
45, Wadai, Tsukuba City
Ibaraki 300-42, Japan

Date Visited: September 28, 1993

Report Author: R.S. Muller

ATTENDEES

JTEC:

S. Jacobsen
R.S. Muller
L. Salmon

HOSTS:

Hiroshi Goto
Minoru Sakata
Tsuneji Yada

The Omron spokesperson for most of the technical exchange was Minoru Sakata, who earlier had been a guest researcher for one year in the MIT laboratory headed by Professors J. Lang and M. Schmidt.

BACKGROUND

The Omron research facility is situated in a rural, park-like area, and has spacious grounds and facilities. The JTEC panel's meeting with Omron began with an overview given by Dr. Tsuneji Yada.

Omron's business in 1991 totaled ¥483 billion, of which ~60 percent was in control components, ~17 percent in electronic fund-handling systems, ~8 percent in office automation, and 6.5 percent in health-care equipment. The panel's hosts provided a company brochure that described the business aspects of Omron. The company has many overseas manufacturing and marketing affiliates. It began operations in 1933, producing switch gear. Omron's goal for 1993 is to develop small, smart control components. Omron has two R&D laboratories. The one in Kyoto focuses on optomechatronics, that is, microlens arrays (thirty-five researchers); the one in Tsukuba focuses on micromechanical sensors (fifty researchers -- roughly twenty-five for MEMS and twenty-five for circuits/systems).

Omron sees its mission served by developing expertise in: (1) fuzzy logic (FL) -- the company has developed controls with FL; (2) life science (this was a bit tenuous in relevance); (3) microcomponents; and (4) computers, controllers, and communications.

A typical Omron system is shown in Figure Omron.1. A concise statement of Omron's plan was presented as: In the longer term, integrate and reduce in size, and in the shorter term, use hybrids and reduce in size.

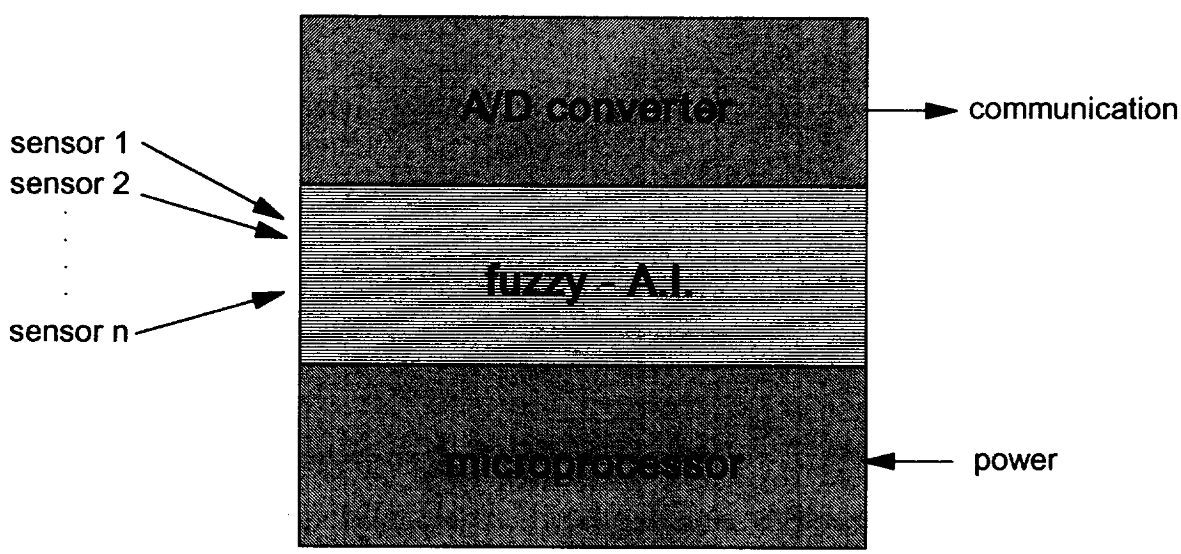


Figure Omron.1. View of typical Omron system.

RESEARCH AND DEVELOPMENT ACTIVITIES

Omron representatives with whom the JTEC panel spoke were participants in the national micromachine technology research program. Their company is one of three (Olympus, Omron, and Terumo) focusing on medical applications. In this program, the Omron team has responsibility for an MMI super-miniature recognition system. Omron showed the panelists a research project for this system in the form of an optical microactuated lens system. Figure Omron.2 shows a concept system of recognition sensor of less than 1 mm OD. Optical elements such as a microlens and a laser diode are mounted on a silicon cantilevered system. Resolution is expected to be -0.5 mm.

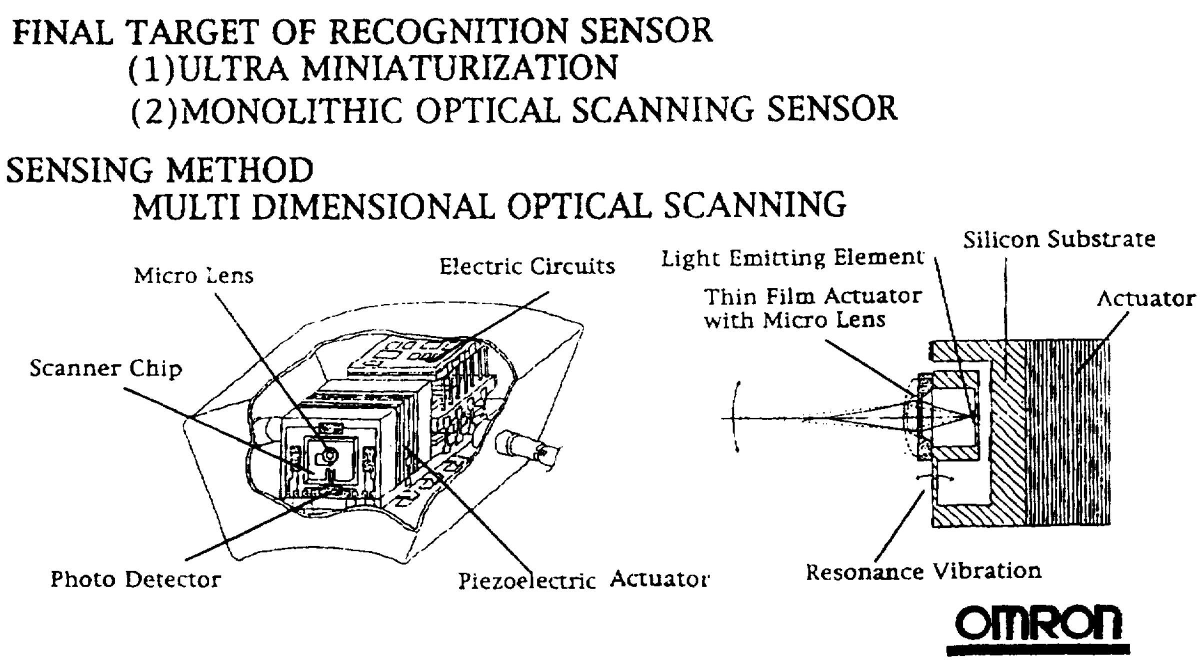


Figure Omron.2. Concept system with a Fresnel lens.

With photodiode readout, this system could function as an accelerometer with optical readout of the position of the cantilevered-seismic mass, which also contains the lens system. Actuation of cantilever is achieved by piezoelectric force. Again, the system fabrication is planned using silicon bulk micromachining with hybrid assembly of the lens. The lens is made of resin that is pressed and cured in a mold made by E-beam exposure of lithography resist into which Ni is deposited.

SUMMARY

Mr. Sakata said that Omron took some time to decide that an MMC project would interest the company. The company ultimately undertook an MMC project to compare and evaluate microtechnologies.

Omron has found bulk Si micromachining more troublesome than expected; difficulties have arisen in the fragility of structures and in the total cost of fabrication and assembly. Mr. Sakata estimated that the Si-based MEMS content of MEMS in Japan is likely to be reduced after three to five years from its present ~10 to 20 percent of total expenditures among all participating companies. It is still Omron's philosophy to pursue silicon processing wherever possible. The company is just now beginning a focus on surface micromachining. Omron sees its biggest advantage in its know-how in batch processing and in its IC experience.

Omron is interested in LIGA development, but no activity is taking place at this time; LIGA's main advantage would be high-aspect ratios. Omron is using anodic bonding for packaging now, but is looking at silicon/silicon bonding as a possible solution to problems with strain. The company is looking toward piezoelectric actuation using PZT thin films, and is collaborating with a Penn State group (Newham) in this area.

Omron "has an impression" that the mechanical properties of polyimide are hard to control, and is not using this material at present. The company is evaluating use of MIT MEMCAD; the panel's hosts stated that "perhaps [they will] begin use next year."

Mr. Sakata explained that the MITI medical application program is very small (~$1 million per year spread among three participants: Olympus in the lead, followed by Omron and then by Terumo).

QUESTIONNAIRE

The following are answers to questions submitted to Omron Corporation before the JTEC panel's visit.

A. Advanced Materials and Process Technology

1. What materials and fabrication techniques are most likely to be used in production for MEMS? Will MEMS continue to be based primarily on silicon IC technology?

Since batch fabrication and characteristics control are key issues in real production line and at least IC process fulfill these requirements, Si-based materials and IC technology must be used in MEMS production.

2. What, in your opinion, is the most important new process or material needed for extending the capabilities of MEMS?

There exist several new materials [that] seem to be important to MEMS. Porous silicon, which has a high oxidation rate, [has] low permittivity, and emits light under suitable conditions, can be applicable to many types of MEMS in many ways.

Piezoelectric thin film like PZT, PSSZT, [and] ZnO are not new, but [are] very attractive, especially for actuators and radiation sensors. Therefore processes to form these films are very important.

3. Are there plans to use X-ray lithography for micromechanics?

We do not have any plan to use X-ray lithography for MEMS.

4. How attractive is the LIGA process for commercial use in MEMS at the present time? How attractive do you expect it to be in five years? Ten years?

Though we do not have any plan to use the LIGA process, it is surely attractive for commercial use now and in the future.

5. If you are pursuing LIGA and LIGA-like high-aspect-ratio structures, what materials are being investigated and why? To what extent do you feel that structures produced using high-aspect etching will be competitive with those formed by plating?

We are not pursuing the LIGA process.

6. What are the prospects for a low-temperature wafer-scale bonding process for MEMS? How low in temperature can we go? Do you feel metal-metal, silicon-glass, or other interfaces are most promising?

Field-assisted room temperature bonding can be realized in five years by adjusting the contents of glass and modifying wafer surface mechanically and chemically. Silicon-glass bonding is better than other combinations, especially sensors and actuators [that] use electrostatic fields.

7. To what extent will silicon fusion play a role in MEMS? Is the area coverage sufficiently high? How much of a real problem is the high bonding temperature?

High bonding temperature is not a big problem because fusion bonding can be done at an early step in the process. Silicon fusion must be a promising process for MEMS, which does not make use of electrostatic fields.

8. What polymeric materials are being explored as photomasks for high-aspect-ratio structures? Is the use of conformal coating processes practical?

We use a conventional AZ1350J resist dipping process for patterning Al on holes of glass wafer to get interconnection, and it works.

9. Polymers for thick photoresist applications are required by MEMS. Are Japanese photoresist suppliers responsive to this need?

[We have] no idea.

10. Do you feel that nested/stacked wafer-level microstructures based on multiple bonding and/or etch-back operations will be feasible within the next five years? Are they important for MEMS?

It seems that nested structure is too complicated to be feasible enough to be used for a commercial-based product.

11. It appears that precision injection molding could play a major role in MEMS. Would you comment on this, please.

[We have] no idea.

12. Are room-temperature superconductors being explored, and if so, what materials and processing techniques are being used?

We are not working on it. We have no idea.

13. Do you expect major advances in micromachining curing the coming decade? Will photo-assist etching or new etch-stops emerge to play a major role? What other technology additions do you consider promising?

[We are] not sure about promising techniques. But the best system partitioning in each application will be made clear during the coming decade, and it will be one of the major advances of MEMS.

14. What are the most important attributes you would insist on for a MEMS processing tool?

Process stability.

B. Sensors and Sensing Microstructures

1. For which sensed variables and types of sensors will MEMS technology have the greatest importance? What are the key advantages of MEMS technology for these sensors?

MEMS technology will still have the greatest importance for mechanical variables like shear force, pressure, and acceleration. The key advantage of MEMS technology is to realize precise sensor dimensions by batch fabrication in fairly small size.

2. Approximately when will the new sensors under development today based on MEMS technology first appear in the marketplace?

It takes at least four years to launch in the marketplace.

3. How can MEMS technology be used to improve existing sensors? What sensor types are likely to be improved the most?

[The cost of] mechanical sensors can be [lowered significantly as a result of] size reduction using MEMS technology.

4. What new sensors can only be developed using MEMS technology? How does MEMS make these new sensors feasible?

[We have] no idea.

5. To what degree is self-testing likely to be possible with sensors? Will this be a major role for MEMS technology?

Adding a self-testing function to a sensor is possible for almost all sensors. This is one of the major factors [for selling] microsensors, but will not be a major role for MEMS technology.

6. After pressure sensors and accelerometers, what is the next major sensor based on MEMS that will be mass-produced in high volume?

Though there are several candidates, like the flow rate sensor and tactile sensor, we are not sure about it.

7. To what degree are feedback readout schemes likely to be important in sensors? Will these feedback schemes involve MEMS?

Only in case of capacitance-type sensors, limited to applications where high sensitivity is necessary, [are] feedback read schemes important. Except for [these] cases, [the] open read scheme should be adopted for simplifying sensors.

8. What are the principal problems in the use of scanning surface probes (e.g., tunneling current) as an approach to high-sensitivity sensor readout? Is this approach likely to find wide application?

The narrow dynamic range may be a problem. This sort of very high sensitivity sensor has only very limited applications.

C. Microactuators and Actuation Mechanisms

1. Can designs using arrays of microactuators achieve large and useful forces? Are there other devices similar to the large optical projection displays that have been reported that can be realized using MEMS technology?

I do not think arrays of microactuators fabricated by MEMS technology have enough force to move something on the same order of size as microactuators efficiently. [However,] biologically-fabricated, much smaller-size actuators may be able to move some biological unit like a cell. Besides, usual MEMS dimensions are not very suitable for microactuators in terms of actuation control because [they are] not under one dominant force regime, that is, large surface force and considerable mass force. Thus, commercial microactuators must be restricted to the application where force is not extracted from the actuator directly, like projection mirror arrays and microgyros. Several arrays of microactuators are presented by Professor Fujita of Tokyo University.

2. Considering their importance to MEMS, in what order of importance would you place the following microactuation mechanisms: shape-memory alloys, electromagnetics, electrostatics, thermal bimorphs, piezoelectric bimorphs, piezoelectrics, electrostriction devices, and phase-change devices? How many of these do you expect will find commercial applications in high-volume products?

Electrostatics, electrostriction and piezoelectric bimorphs are the most important microactuation mechanisms. These three have the possibility [of being] applied to commercial applications.

3. What are the most reasonable candidates for prime movers for microactuation?

Prime movers are optical applications like projection mirror.

4. To what extent can sticking problems due to surface forces be suppressed in microactuators? Will these problems seriously constrain the practical application of microactuators based on narrow gaps?

In [the] fabrication process, [the] sticking problem is a major problem [that] we have to solve. In actuation, a stick-prevent[ion] approach can be adopted. Therefore, [the] sticking problem will not limit practical application of microactuators.

5. What is the most promising candidate for a microrelay? Where are such devices most likely to be used?

The most promising candidate for a microrelay might be an electrostatic force. We once tried to develop an electrostatic microrelay and quit because of its poor characteristics. I am really not sure if we should use MEMS technology to develop microrelays rather than taking an approach of reducing the size of conventional electromagnetic relays. This kind of relay is likely to be used as a small signal relay for telephone switchboards.

6. What are the main design issues in microfluidic systems? Where will such systems find their primary application?

I suppose the most important design issue is dimension and charge control of channel surface.

7. What designs are most likely to be adopted for practical microvalves and micropumps? What is holding up the practical realization of these devices?

Professor Esashi's microvalve and micropump design (hybrid type) is a strong candidate. Packaging is the issue that may be the biggest problem in fabricating practical devices.

D. Sensor-Circuit Integration and System Partitioning

1. Will MEMS technology lead to complete microminiature "instruments on a chip?" For what types of instruments?

Yes, there will be many types of "instruments on a chip" led by MEMS. An example is the flow measurement system developed at Michigan University.

2. Will MEMS technology combine sensors and actuators into complete control systems? If so, what types of control systems will be most affected?

MEMS will be likely to combine these two in special cases such as a system of optical sensors (or CCD devices) and optical scanning mirrors.

3. Are systems involving sensors, actuators, and embedded microcontrollers likely to be realized in monolithic form or will they be hybrid? What factors are driving for monolithic integration for what types of products?

Those will be hybrid at first, and after integration techniques [for] sensors and other devices become solid, those will be realized in monolithic form. Parasitic capacitance reduction is a major motivation for realizing monolithic surface micromachined capacitance-type pressure sensors and accelerometers.

4. What levels of integration (transistor count) are we likely to see on MEMS chips by 1995? By the year 2000? Are full microprocessors needed or realistic?

By 1995, we can see at least around 300 transistors, and 1,000 transistors by 2000. Because integration of many devices makes its yield go down drastically, [we are] not sure if full microprocessor integration is realistic.

5. To what extent will embedded microcontrollers be used in (possibly hybrid) integrated sensing nodes -- high-end devices only, or will they eventually become pervasive in even low-end products?

The embedded microcontrollers will be used in only high-end devices. Application to low-end devices may not fulfill cost requirements.

6. What are the prospects for adopting sensor bus standards, at least in specific industries (automotive, process control, HVAC)? How important is the evolution of such standards to the development of MEMS?

We do not consider adopting sensor bus standards so much now. Our sensors have their own input/output specifications. They are adjusted to each application.

7. Will sensor calibration continue to be done in hardware (laser-trimming or EPROM), or will it evolve to digital compensation in software? Is this an important issue in MEMS development?

In the future, calibration will be carried out by software rather than hardware. It is also an important issue considering system partitioning.

8. Will a few standard processes emerge to dominate sensor-actuator-circuit integration, or will widely divergent processes continue to be the norm in MEMS? What issues will determine the answer to this question?

[The] system partitioning issue will lead [to] its answer.

E. Advanced Packaging, Microassembly, and Testing Technology

1. What are the general directions for progress in packaging MEMS? What are the principal challenges here?

There are two principal challenges. One is to obtain the reliable interconnections. The other is not to effect MEMS mechanically, electrically, and chemically.

2. What will be the application and impact of MEMS on the packaging of sensors?

MEMS will improve interconnection between chips and devices.

3. How much of a problem is die separation for surface micromachined devices? Is this optimally performed after release?

We are not working on surface micromachined devices now.

4. How important are the chip-level packaging schemes now under development to MEMS devices and systems? Is the increased process complexity worth it?

Chip-level packaging is the most important technical issue in MEMS packaging. It is worth pursuing this technique.

5. Are common packaging approaches across many types of devices feasible or will packaging continue to be very application specific?

Packaging will keep having significantly large application-dependency unless a chip-level packaging technique is developed.

6. What viable techniques exist for coupling force from integrated microactuators while protecting the device from hostile environments? Can mechanical microactuators only be used inside hermetic packages?

Possibilities are electrostatic or magnetic coupling. Using these kinds of noncontact coupling, microactuators can be inside of hermetic packages.

7. To what degree should MEMS continue to focus on monolithic silicon microstructures, and to what degree do you think it is really better suited to milliscale integration with components combined using microassembly techniques?

[We have] no idea. It really depends on the purpose of individual MEMS R&D. In case the purpose is to figure out what MEMS should be in the future, also monolithic types should be investigated. On the contrary, if the project aims to develop commercial MEMS, the microassembly approach must be taken.

8. Are there microassembly techniques that can be sufficiently automated to make millielectromechanical devices in high volume at moderate or low cost? What are the generic barriers to such devices and techniques?

[We have] no idea.

9. What techniques are available for testing MEMS structures after encapsulation/packaging? What happens when they are no longer viewable?

Now we are testing sensors only electrically after [they are] packaged. Therefore, we can get only secondary information of sensor structure through its response. We do not have any other method now.

F. MEMS Design Techniques, Applications, and Infrastructure

1. The term "MEMS" has many meanings. Could you tell us your interpretation?

MEMS means components that include critical parts that are micron order-of-size and/or fabricated with micron-order preciseness.

2. Is there a MEMS technology driver equivalent to the DRAM in the IC industry? If so, what is it?

[We have] no idea.

3. Is the integrated-circuit industry the principal application driver for MEMS? If so, what are the alternative drivers during the next decade, if any?

[We have] no idea.

4. In what sensor application areas do you see MEMS technology having the greatest importance? (Examples might be: automotive, medical, robotics, consumer products, etc.) What are the key advantages of MEMS technology for these applications?

Automotive and medical areas. Key advantages are size reduction and dimension control.

5. What will be the application and impact of MEMS on the interfacing of sensors to the environment?

Because MEMS are usually very small, [they do] not affect the environment so much, and we can measure variables without giving effective disturbance to [the] environment.

6. Looking ahead five years, what new MEMS-based sensors and sensor applications do you anticipate?

[We have] no idea.

7. In what time frame do you anticipate MEMS technology having the most impact on sensor products (for example, three years, five years, ten years, etc.).

Three years.

8. What is the prognosis for MEMS foundries? Are they needed? What technologies would need to be present in a MEMS foundry?

[We have] no idea. But microassembly technology will be essential for MEMS foundries.

9. What is the state of the art in MEMS reliability? Where are the principal problems?

Reliability is still not good. The principal problem we have to solve is durability.

10. What is the "state of the art" in MEMS designability? How important are CAD tools for MEMS? Do you have an active CAD effort for MEMS in your organization?

MEMS designability now is very low. Therefore CAD tools are very important, and we have a project on it.

11. What priority would you place on the creation of a central MEMS database of material and design parameters? Does your organization have an active project in this area?

The priority is very high. We also have a project on it.

12. How much funding is being directed into MEMS research and development in your organization? What percentage is this amount of the total R&D budget?

[We] cannot comment on it.

13. In your view, is enough funding available to support MEMS research in Japan? In the world? Are the principal bottlenecks to more rapid progress money or ideas?

There is not enough funding to support MEMS R&D in Japan. I have no idea as to [whether there is enough] world funding. Ideas for application are very critical and [are] a major bottleneck.

14. What portions of your R&D funding for MEMS comes from internal, government or other sources? Has increased government funding had a major impact in your organization?

[We] cannot comment on the portion. Increased government funding had an impact in our organization.

15. What percentage of your research is directed toward specific products? Toward basic research?

The percentage of basic research is around 5 percent.

16. What emerging technologies do you see as having the largest influence on MEMS and why (i.e., LIGA, superconductors, submicron ICs, piezoelectrics, thin-film magnetics, etc.)?

Piezoelectric thin films [will] have [an] influence on MEMS, especially for actuators.

17. What are the principal barriers to the success of MEMS?

Difficulties in finding good applications for MEMS is the principal barrier.

18. What do you believe to be the major competitive technology alternative to MEMS?

[We have] no idea.

19. Are patents a key to commercial success or are base technology skills more critical?

Both are key factors to commercial success.

20. The first generation of university graduates who specialized in MEMS are now finishing their degrees. Are employment opportunities for these students plentiful in Japan?

Yes.

Site: **Seiko Instruments, Inc.**
Takatsuka Unit
563, Takatsuka-Shinden, Matsudo-shi
Chiba 271, Japan

Date Visited: September 29, 1993

Report Author: H. Guckel

ATTENDEES

JTEC:

H. Guckel
K. Wise

HOSTS:

Chuzo Takahata	Director, Corporate R&D, SII
Tatsuaki Ataka	General Manager, Research Laboratory for Advanced Technology, SII
Hideo Hirama	General Manager, Precision Instruments Department, Consumer Problems Division, SII
Masayuki Suda	Research Laboratory for Advanced Technology, SII
Sadazumi Shiraishi	Manager, Corporate R&D Planning Department, SII
Kazuyoshi Furuta	Supervisor, Device Development Section Device Development, Department No. 2, SII

BACKGROUND

The meeting at Seiko began with an explanation of the Seiko Group by Mr. Chuzo Takahata. He explained the corporate structure of the Seiko Group, which consists of four companies: Seiko Corporation, Seiko Instruments, Inc., Seiko Epson Corporation, and Seikosha Co., Ltd. The four companies are independently operated, but function as a unit in the design, production, and marketing of Seiko time pieces. The Seiko Corporation markets the watches produced by Seiko Instruments, Inc. and Seiko Epson, and the clocks produced by Seikosha. Sixty percent of net sales originate from this business. Other business activities are handled independently by the four companies.

The JTEC panel's visit was with Seiko Instruments, Inc., or SII. This company is in four major product areas:

1. Consumer products	46 percent of sales
2. Information devices and systems	19 percent of sales
3. Electronic components	26 percent of sales
4. Production equipment	9 percent of sales

SII employs 5,900 people with 1993 sales of roughly $1.5 billion.

RESEARCH AND DEVELOPMENT ACTIVITIES

Mr. Tatsuaki Ataka explained the product lines in some detail. He stated that SII was an early contributor to CMOS technology, and produces many integrated circuits, liquid crystal displays, and thermal print heads. SII also markets these devices, a very sophisticated ULSI design system, electronic design automation systems, and a mechanical CAE/CAD/CAM system. These software-oriented systems are supported by plotters, digitizers, and color-image scanners. Remote communication systems are used for products such as personal pagers and restaurant-ordering systems.

The production equipment area extends from spectrophotometers to X-ray fluorescent equipment to CNC automatic grinders to magnetically levitated turbopumps to focused ion beam repair systems. SII produces its own scanning probe microscope system, which includes probe, signal, and graphics processing.

In the materials area, SII markets microbatteries, rare earth magnets, and micromotors. In this last category are several AC, DC and ultrasonic motors with reduction gears. Very impressive is a three-phase stepping motor with a 60° stepping angle with a maximum pull-in frequency of 1,300 pps. The device has a diameter of 2.8 mm, is 5 mm long, and can be connected to a 1:23 reduction gear via a 0.5 mm output shaft. Output torque can be as high as 12 mg-cm at low frequency. Mr. Hideo Hirama explained that the cost of the motor would be near $1,000. A related device is a microsolenoid, with an outer diameter of 2 mm, a maximum stroke of 0.6 mm, and an output force of 1.5 g force.

SII makes several sensors. A glucose and liquid flow sensor use quartz resonators, in which SII is very experienced. The company produces capacitive pressure transducers and cantilevers for atomic force microscopes. SII's engineers are involved in squids for magnetic sensors that they will leverage into a system. In micromechanics, SII works on micromotors and micrograppers. The company has worked with Microparts in Germany to produce gears via LIGA processing. Discussions with the SII Group indicated that its interest in LIGA persists.

SUMMARY OF DISCUSSION

Mr. Ataka stated that SII has no specific target for MEMS. The possibility of using MEMS for a processing tool by, for instance, developing better focused ion beam sources, was discussed briefly. This was followed by an interesting discussion of an SII concept that was called Dr. Chip. In this concept, a watch-like structure is used to monitor the medical disposition of the watch wearer. The information is communicated to a remote doctor who reacts to the measured data. This type of system perfectly matches SII skills and interests, and could become a major project in Japan, where health care costs, according to the *Japan Times*, can exceed $3,000.00 per year per patient.

REFERENCES

A full description of SII is available in brochure form.

Specifications in the form of product bulletins are available for the MEMS devices.

Site:	**SORTEC Corporation** **Tsukuba Research Laboratory** **16-1 Wadai, Tsukuba-chi** **Ibaraki 300-42, Japan**
Date Visited:	September 28, 1993
Report Author:	H. Guckel

ATTENDEES

JTEC:

H. Guckel
C. Uyehara
K. Wise

HOSTS:

Takeshi Kishimoto	Mitsubishi Electric
M. Nishimura	Canon, Inc.

BACKGROUND

Mr. Takeshi Kishimoto explained the basic purpose, organization, and funding of SORTEC. SORTEC is a synchrotron facility that has a defined charter for the period 1986 to 1996. The charter involves ULSI lithography with a 1993 to 1995 goal of 0.15 μm linewidth with 0.04 μm overlay. For this purpose, it is funded at ¥14.3 billion over a ten-year period, and has a staff of eight administrators and twenty-two scientists. There are thirty membership companies. The synchrotron is a 1 GeV machine with a Linac injector into a booster synchrotron that feeds the storage ring. The storage ring is now operated at 500 mA beam current in a constant current mode, 1 to 2 percent accuracy, for more than twenty-five hours. The critical wavelength for the machine is 15.5 Å. The machine supports users from Monday to Thursday, and uses Friday for maintenance and development.

RESEARCH AND DEVELOPMENT ACTIVITIES

The synchrotron SORTEC-1 can support eight beam lines; there are now four active beam lines. One of these is used with a Panasonic stepper, which has achieved alignment at 3σ of 240 Å. The exposure and alignment times are large. A second beam line is used with a Schwarzschild objective for projection lithography at 32:1 reduction. This system has produced 500 Å line and spaces into PMMA.

In the ULSI area, photoresist tests are performed with 0.6 μm of AZ-PH 100 Hoechst negative resists. The mask is formed on a silicon nitride blank with 90 percent transmission at 6,330 Å, which is fabricated by Oki Electric. The absorber is evaporated tantalum. This material when evaporated at an angle can produce linewidths to 800 Å.

The visit to the facility included a tour of the booster synchrotron, the storage ring, and the stepper clean room area.

SUMMARY OF DISCUSSION

Discussions with Mr. Nishimura and Mr. Kishimoto included two main topics: the use of synchrotron radiation for high-aspect-ratio processing and the need for higher energy radiation for LIGA-like processing.

In the high-aspect-ratio area, Mr. Nishimura showed results of 0.7 μm lines and spaces in 5 μm thick photoresist. Mechanical failure in these geometries was assigned to the drying process after wet processing of the photoresist. This failure was related to surface tension forces, with additional complications due to spin drying.

In a very interesting discussion, deep X-ray lithography for micromechanics became the major topic. SORTEC researchers have attempted to expose LIGA-like photoresist layers in a very exploratory manner. Exposure times were long which is not surprising for this type of ring. Modification of the synchrotron via an insertion device is somewhat hampered by the fact that maximum straight section length is 2 meters.

Mr. Nishimura and Mr. Kishimoto indicated that they were aware of the attempts by the Fujita Corporation, a major Japanese Construction Company, to build and operate a high energy ring as a private enterprise, an effort that Fujita Corporation representatives had described earlier in a meeting at the Wisconsin Center for Applied Microelectronics in Madison, Wisconsin.

REFERENCES

Atoda, N., et al. 1992. "Present Status of SORTEC SR Facility." *Rev. Sci. Instrum.* 63(1).

Kishimoto, T., et al. 1993. "Present Status of SORTEC 1-GeV 500 mA SR Source Facility." Paper presented at the 9th Symposium of Accelerator Science and Technology. Tsukuba, Japan.

Morigami, M., et al. 1993. "Exposure and Resist Process Condition Dependence of Replicated Pattern Accuracy in SR Lithography." *SPIE Proceedings*, Vol. 1924, March.

Site: **Tohoku Gakuin University**
Department of Electrical Engineering
13-1 Chuo-1, Tagajo
Miyagi-ken 985, Japan

Date Visited:

Report Author: S. Jacobsen

ATTENDEES

JTEC:

H. Guckel
S. Jacobsen
L. Salmon
K. Wise

HOSTS:

Dr. Mitsutera Kimura	Tohoku Gakuin University
Dr. Masayoshi Esashi	Tohoku - Sendai
Mrs. Cleopatra Cabuz	Tohoku - Sendai
Dr. Seung-Ki Lee	Tohoku - Sendai

NOTES

Dr. Mitsutera Kimura has no permanent staff and uses student workers in the laboratory. He has stated that funds and lack of staff are a handicap to his progress. Despite these limitations, Dr. Kimura's laboratory is well laid out and very clean given that it is still in development. Most of the equipment has been donated, but seems to serve his needs for the present.

Dr. Kimura's laboratory mostly focuses on the development of microcircuits, which include some micromachining. The goals of the laboratory include education, technology development, and development of products intended to be spun off to commercial ventures. Eleven projects were discussed.

Dr. Kimura's Projects

1. Silicon etched wave guide (1980)

   This work focussed on the generation of optical wave guides on both sides of a groove etched in silicon. This method was also mentioned in relation to generating microair bridges.

2. Miniature optoelectric transformer

   The miniature optoelectric transformer concept included a solar cell, an electrical transformer, and a laser diode emitter integrated onto a single silicon chip.

   The photocell was configured for direct interaction with a core of optical fiber. The geometry included a toroidal depression with a raised center appropriate for docking with the fiber core.

   The transformer included a two-turn primary and a two-turn secondary (a later design will include a many-turn secondary). Dr. Kimura claimed an interesting method for deep etching to form the coils.

   The laser diode emitter was designed, but a real system has not been fabricated or tested. Specific applications were not identified nor has a complete system been fabricated.

3. Schottky tunneling transistor

   Dr. Kimura claimed to have achieved very low threshold devices (i.e., no power drop), which could be very good for solid state relays and other devices.

4. Field emission vacuum magnetic field sensor

   A system was discussed that measures the local magnetic field by detecting the magnetically induced deflection of an electron stream. The concept was very interesting; however, with deeper examination, the JTEC team had serious questions regarding its practicality. The system required very large electric field gradients (20 kV per cm), and the use of Dr. Kimura's special zero threshold transistor.

5. Microheater made of heavily boron-doped single crystal silicon beam (1981)

6. Schottky barrier thermistor

7. Infrared sensor with microair bridges of a-Si(h) film

8. Anemometer-based flow sensor

9. Vacuum sensor

10. Humidity sensor

11. Accurate compensation method for the ambient-temperature-dependent deviation of thermistors

Dr. Kimura has focused on developments that have commercial markets. He patents his work and collaborates with industrial groups to commercialize results. Dr. Kimura indicated that in Japan, professors are free to execute patents independently of the university and to arrange for industrial contracts that commercialize products and pay royalties directly to the professors.

Site:	**Tohoku University** **Semiconductor Research Institute** **Dept. of Mechatronics and Precision Engineering** **Laboratory for Microelectronics (Super Clean Room), Research Institute of Electrical Communication** **Aza Aoba, Aramaki, Aoba-ku** **Sendai 980, Japan**
Date Visited:	October 1, 1993
Report Authors:	K. Wise and H. Guckel

ATTENDEES

JTEC:

H. Guckel
S. Jacobsen
L. Salmon
K. Wise

HOSTS:

Masayoshi Esashi	Professor, Department of Mechatronics and Precision Engineering
Dr. Seung-Ki Lee	JSPS Visiting Fellow, Department of Mechatronics and Precision Engineering
Mrs. Cleopatra Cabuz	Assistant Professor, on leave from the Faculty of Electronics and Telecommunications, Polytechnical Institute of Bucharest, Romania

NOTES

The JTEC team's first visit was to the Semiconductor Research Institute, where there is extensive research underway in high-speed compound semiconductor devices and advanced semiconductor process technology. Much of the work was centered around the static induction transistor (SIT) structure pioneered by Nishizawa (1986) and is aimed at the delay range from 100 fS to 1 pS (see also Yusa et al. 1992). The institute's laboratory included at least ten molecular-layer epitaxy growth systems and numerous surface analysis tools, including QMS, RHEED, AES, and XPS. The laboratory was clean, well organized, and very well equipped. It was probably the equal of any in the United States, and was impressive both for its facilities and for many of its research results.

The team next traveled to the micromachine laboratory of Professor Masayoshi Esashi. This laboratory consists of forty-three people. In addition to Dr. Esashi, there are Associate Professor Shuichi Shoji, three assistant professors, one postdoctoral researcher, fourteen researchers on leave from various companies, twenty-one students (four in the doctoral program, eight in the master's program, and nine undergraduates), one technician, and one secretary.

Efforts are focused in five areas:

- Packaged sensors
  (accelerometers, resonant sensors, vacuum packaging)

- Materials, integrated circuits, and micromagnetic devices
  (chemical and flow sensors, actuators, zero-TC piezoresistors)

- Electrostatic microactuators, RIE, and nanofabrication
  (High-rate RIE, molecular-layer epitaxy, STM, microvalves)

- Catheters, microassembly, and optical measurements
  (Active catheters, fiberoptic pressure sensors, tactile sensors, laser-based microfabrication)

- Semiconductor Research Institute projects
  (SIT thyristors, CMOS SITs, metal-GaAs contacts using WCVD)

In all, a total of forty projects are represented by these efforts. This is a very impressive number to be directed by a single faculty member. It was also interesting that in Japan the faculty members each independently have their own laboratories (which is similar to arrangements in Europe) and do not share combined facilities, as is usually done in the United States. A comparable laboratory in the United States would also have more permanent technical staff and perhaps more doctoral students but would sadly have many fewer industrial residents, making technology transfer much more of a problem. The industrial residents here represented individuals primarily from non-semiconductor companies who would be producers of microsystems for automotive, medical, and other applications. Funding for most of this work comes from the Ministry of Education.

Professor Esashi described some of the different research projects currently underway. Many devices from this laboratory have been successfully commercialized in the past, including two ion-sensitive field-effect transistors for measuring pH and pCO_2, and a capacitive pressure sensor (Matsumoto, Shoji, and

Esashi 1990). There has been considerable work on vacuum-based packaging of sensors, including pressure devices (Henmi et al. 1993) and accelerometers (Esashi 1994; Matsumoto and Esashi 1992; Matsumoto and Esashi 1993). Research projects are also addressing a broad array of other topics, including resonant devices (Yoshimi et al. 1992; Cabuz et al. 1993), microactuators (Minami, Kawamura, and Esashi 1993), dry micromachining using RIE at low-temperatures (Takinami 1992), bonding (Esashi, Ura, and Matsumoto 1992), feedthroughs, and sensor-circuit integration (Nagata et al. 1992). These projects were all very well done and the work is world class. For example, work is underway on an active catheter equipped with multiple sensors and with distributed actuators along its length to allow the catheter to be mechanically bent as required for insertion in the cardiovascular system. The target size for this catheter is 1 mm OD. The integration of circuitry with sensors is viewed as a dominant trend, even though most existing sensors still operate using hybrid interface electronics. A new thrust area in this laboratory is work on nanofabrication, using techniques such as epitaxy and scanning tunneling microscopy to create new structures as well as efforts on microassembly tools for devices such as the active catheter.

The JTEC team toured Dr. Esashi's laboratory facilities, which are distributed in several nearby buildings. These were extensive and very impressive, covering a very broad range of capability. The wafer size in this facility is 20 mm, allowing the use of small process chambers in many cases. There were dedicated facilities for laser-assisted etching, in-process monitoring of anisotropic silicon etching, vacuum-sealing of devices, long-term testing of resonant structures, deflection measurements to 1 Å, cryogenic RIE-based micromachining, CVD of several materials, and circuit fabrication. The facilities were well organized and represented an impressive investment of time equal to any in the United States.

The team's last stop was at the Laboratory for Microelectronics (Super Clean Room), Research Institute of Electrical Communication, directed by Professor Yasuji Sawada. Aimed at exploring semiconductor manufacturing techniques and device structures for the next century, this facility is a major resource probably larger and better equipped than any university facility in the United States. Built at an estimated cost of ¥1 billion (building only), and with an annual budget for utilities and materials/supplies of about ¥200 million, this clean room is particularly remarkable in that it runs with only two staff members and one technician. There are a total of 232 users of the clean room, which offers a broad array of fabrication equipment in an environment estimated at Class 1. Most of the students here are at the B.S. and M.S. degree levels. The facility is in part maintained by these students and in part by industrial visitors. In this facility, 33 mm wafers are processed. The laboratory has a full range of process equipment, including facilities for mask making, ion implantation (200 keV), extensive surface analysis (XPS, RHEED, SIMS, and STM), and specialized processes such as CVD aluminum. The facility is entirely built with a perforated floor and is composed of three levels.

Overall, the projects and facilities at Tohoku University were outstanding and state of the art. The university is clearly having important impacts and is exerting leadership in the fields of semiconductor electronics and MEMS on a worldwide basis.

REFERENCES

Cabuz, C., S. Shoji, E. Cabuz, K. Minami, and M. Esashi. 1993. "Highly Sensitive Resonant Infrared Sensor." *Digest Int. Conf. on Solid-State Sensors and Actuators.* C6-5.

Esashi, M. 1994. "Sensor for Measuring Acceleration." In *Mechanical Sensors*, ed.N.F. de Rooij, VCH Pub.

Esashi, M., N. Ura, and Y. Matsumoto. 1992. "Anodic Bonding for Integrated Capacitive Sensors." *Proc. IEEE MEMS Workshop.* Pp. 43-48.

Henmi, H., K. Yoshimi, S. Shoji, and M. Esashi. 1993. "Vacuum Packaging for MicroSensors by Glass-Silicon Anodic Bonding." *Digest Int. Conf. on Solid-State Sensors and Actuators.* C1-2.

Matsumoto, Y., and M. Esashi. 1992. "Integrated Capacitive Accelerometer with Novel Electrostatic Force Balancing." *Digest of the 11th Sensor Symposium.* Pp. 47-50.

Matsumoto, Y., and M. Esashi. 1993. "Low-Drift Integrated Capacitive Accelerometer with PLL Servo Technique." *Digest Int. Conf. on Solid-State Sensors and Actuators.* C13-5.

Matsumoto, Y., S. Shoji, and M. Esashi. 1990. "A Miniature Integrated Capacitive Pressure Sensor." *Abstracts of the 22nd Conf. on Solid-State Devices and Materials.* Pp. 701-704.

Minami, K., S. Kawamura, and M. Esashi. 1993. "Distributed Electrostatic MicroActuator." *Digest Int. Conf. on Solid-State Sensors and Actuators.*

Mizoguchi, T., Y. Ohta, and M. Takayama. 1986. "SIT Image Sensor: Design Considerations and Characteristics." *IEEE Trans. Electron Devices.* 33, June: 735-742. Also, many other publications based on SIT structures.

Nagata, T., H. Terabe, S. Kuwahara, S. Sakurai, O. Tabata, S. Sugiyama, and M. Esashi. 1992. "Digital Compensated Capacitive Pressure Sensor using CMOS Technology for Low-Pressure Measurements." *Sensors and Actuators.* A34:173-177.

Nishizawa, J., T. Terasaki, and J. Shibata. 1986. "Field-effect Transistor versus Analog Transistor (Static Induction Transistor)." *IEEE Trans. Electron Devices* 22, April: 185-197.

Yoshimi, K., K. Minami, Y. Wakabayashi, and M. Esashi. 1992. "Packaging of Resonant Sensors." *Digest of the 11th Sensor Symposium.* Pp. 35-38.

Yusa, A., J. Nishizawa, M. Imai, H. Yamada, J. Nakamura, M. Takinami, K. Minami, and M. Esashi. 1992. "High-Speed Directional Low-Temperature Dry Etching for Bulk Silicon Micromachining." *Digest of the 11th Sensor Symposium.* Pp. 15-18.

Site:	**Toyota Central R&D Laboratory** **41-1 Aza Yokomichi** **Oaza Nagakute** **Nagakutecho, Aichi-gun** **Aichi 480-11, Japan**
Date Visited:	October 1, 1993
Report Author:	J. Giachino

ATTENDEES

JTEC:

J. Giachino
G. Hocker
R. Muller
C. Uyehara

HOSTS:

Dr. Osami Kamigaito	President and Chief Operating Officer
Dr. Isemi Igarashi	Research Scientist
Hiroshi Nagase	Device Div., Division Staff, LSI Design Lab Laboratory Manager
Susumu Sugiyama	Senior Researcher, Laboratory Manager, Device Development Lab.
Dr. Masaharu Takeuchi	Senior Researcher, Manager Physical Sensor Lab.
Dr. Osamu Tabata	Silicon Sensor Group, Group Leader
Ryouji Asahi	Surface Science Group
Toru Koyam	Senior Engineer, Section Manager, Research Administration
Junko Nakashima	Research Administration

BACKGROUND

Toyota showed a video tape that described the company and the work being done at the Central Research Laboratory. There are 990 employees at the laboratory, 75% of whom are scientists and engineers. The research funding is 50% for the needs of the stock holding companies and 50% to explore new ideas, with an average research time (concept to out of research) of three years. The normal research group is three to seven people. Approximately 10 researchers are working on silicon physical sensors and 10 researchers on gas sensors. The research is mainly for automotive sensors.

A group to develop medical sensors was started in June 1993 under Dr. Igarashi. The target is to develop silicon based sensors for in vitro. The Physical and Chemical Research Institute is funding this work, not the Central Research Laboratory.

RESEARCH AND DEVELOPMENT ACTIVITIES AND DISCUSSION

MEMS research at Toyota Central R&D Laboratories is focused on silicon microsensors.

Researchers at Toyota Central R&D are studying magnetic materials and pyroelectric materials. The major area of this materials research is sensors. They are also doing work on surface micromachining processes using thin films as the construction material (because of the compatibility with LSI and small size). The thrust is toward integrated sensors. Their main IC process is CMOS, and they want to minimize any changes to the process. They have been using silicon nitride thin films for structures.

The mechanical engineers are still concerned about the reliability of polysilicon. They are looking for a new material which can be of structural use for automotive sensors. They think that SiC is a possible replacement for silicon nitride and/or polysilicon. In their view, the barriers to new sensor materials are the photolithography (etching), temperature needs and potential contamination of the IC process.

Sensor packaging is a major concern; Toyota is looking for on-chip packaging such as a vacuum seal.

In addition to physical sensors, researchers are working on chemical sensors based on fine particle and thin film.

Toyota Central R&D Laboratories is not doing much work on microactuators. Research personnel there believe that the first application of a microactuator will be in a closed loop system with a sensor. They are concerned about assembly problems with LIGA fabricated parts.

Toyota is not involved in the MITI project. Even though Nippondenso and Aichi -- companies with which they have close ties -- are in the program, information is withheld from Toyota Central R&D Laboratories.

Site: **University of Tokyo**
Institute of Industrial Science
7-22-1 Roppongi Minato-ku
Tokyo 106, Japan

Date Visited: September 27, 1993

Report Author: R.S. Muller

ATTENDEES

JTEC:

J. Giachino
B. Hocker
S. Jacobsen
R. Muller
L. Salmon
C. Uyehara
K. Wise

HOSTS:

Fumio Harashima	Professor; Director General, Institute of Industrial Science
Felix Moesner	Graduate Student, Fujita Group
Manabu Ataka	Graduate Student, Fujita Group

BACKGROUND

The following comments are from an interview with Director General Fumio Harashima that preceded the team's visit to individual laboratories.

The Institute of Industrial Science (which consists of twelve institutes) is a part of the University of Tokyo. The institute was founded in 1949 as a research establishment for engineering at Japan's most prestigious university, which was established in 1877. The institute carries out only graduate teaching and research with ~350 students, ~95 faculty members, ~72 research associates, ~118 clerical staff members, and ~83 administrative staff members. The director general serves a three-year term and is generally selected from among the full professors. Professors teach one semester course in a year, and the institute typically hosts ~200 visitors. The budget for 1993 was $60 to $70 million; 40 percent of this was used for salaries. Fifty percent of the budget comes from the national government, and 50 percent comes from research contracts (industrial). All faculty at IIS-UT are tenured.

The institute is further divided into nine departments and research centers. Of special relevance to the JTEC visit is the Research Group of Excellence on Micromechatronics, which consists of the laboratories of faculty members whose work centers on MEMS. Those faculty in the research group are five IIS-UT regular professors augmented by two Toshiba Chair professors who are at IIS-UT for a year or longer. The five IIS-UT professors and the specialties of their research laboratories are:

1. Professor Hiroyuki Fujita (group leader, EE Dept.): microelectromechanical systems by IC processes

2. Professor Takayoshi Masuzawa (ME Dept.): micromachining

3. Professor Hideki Kawakatsu (ME Dept.): nanotechnology applied to scientific instrumentation

4. Professor Hideki Hashimoto (EE Dept.): man-machine interface in the microenvironment

5. Professor Toshiro Higuchi: precision machinery engineering, ultrafine mechatronics

The two Toshiba-chaired visitors are:

1. Professor Hannes Bleuler (ME Dept., visiting from ETH, the Swiss Federal Institute of Technology): active microlevitation

2. Professor Ren C. Luo (visiting from the Robotics Center at North Carolina State University): microsensors for advanced control. During the visit, the team learned that apparently Professor Luo had completed his visit and returned to the United States effective 1 September 1993.

Graduate student Felix Moesner acted as host in Professor Fujita's absence, and took the JTEC team to Director General Harashima, then to Kawakatsu and Masuzawa laboratories before the visit to the Fujita laboratory. No professors were present.

RESEARCH AND DEVELOPMENT ACTIVITIES

The first visit was to the Kawakatsu laboratory, where metrology based upon scanning tunneling microscopy is being developed; the idea is to position an xy table using the lattice spacing of C atoms in a lattice for the scale of reference. In the same area, the team viewed research on a laser-guided magnetic suspension system being carried out under the supervision of Professor Hannes Bleuler (of ETH, Zurich).

In the Masuzawa laboratory, the focus was on "wire electric discharge grinding" (WEDG), which is a technique for machining microholes and microshaping to form nozzles and other shapes down to ~4 micron diameters.

The Fujita laboratory visit was notable for its total concentration on IC-based processing. Figures IIS.1 and IIS.2 show the activities and facilities. The consensus of the group visiting was that the laboratory is very crowded and has what would be considered in the United States significant safety hazards. Despite the limited facilities, Fujita's group is outstandingly productive in research.

SUMMARY

The IIS-UT capacity to transform and reform its parts to address a broad research program is shown up positively by the Fujita-led Research Group in Micromechatronics. Both Professors Fujita and Kawakatsu provided selected answers in writing to the JTEC questionnaire on MEMS. The answers from Professor Fujita are summarized below:

- Silicon is and will continue to be the major MEMS material for some time. Other materials such as SMAs are of interest mainly for actuation. Researchers at IIS-UT are studying YBa-Ca-0 for levitation of bearings and linear actuators.

- They believe arrays of actuators are a useful, good idea. They do not favor electromagnetics, thermal bimorphs, electrostriction, or phase-change devices for actuation. Telecommunications seems to be a feasible area for MEMS applications.

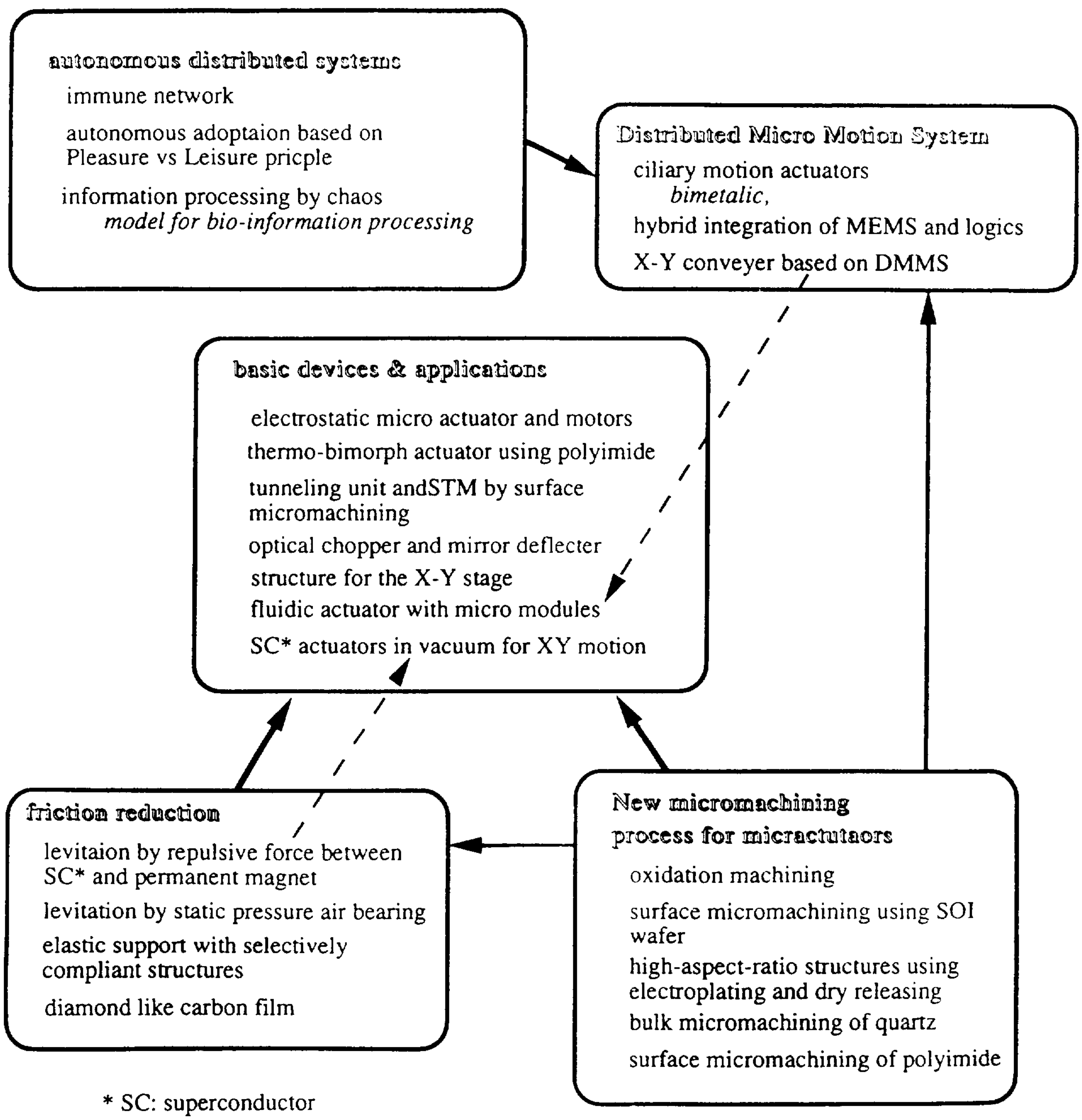
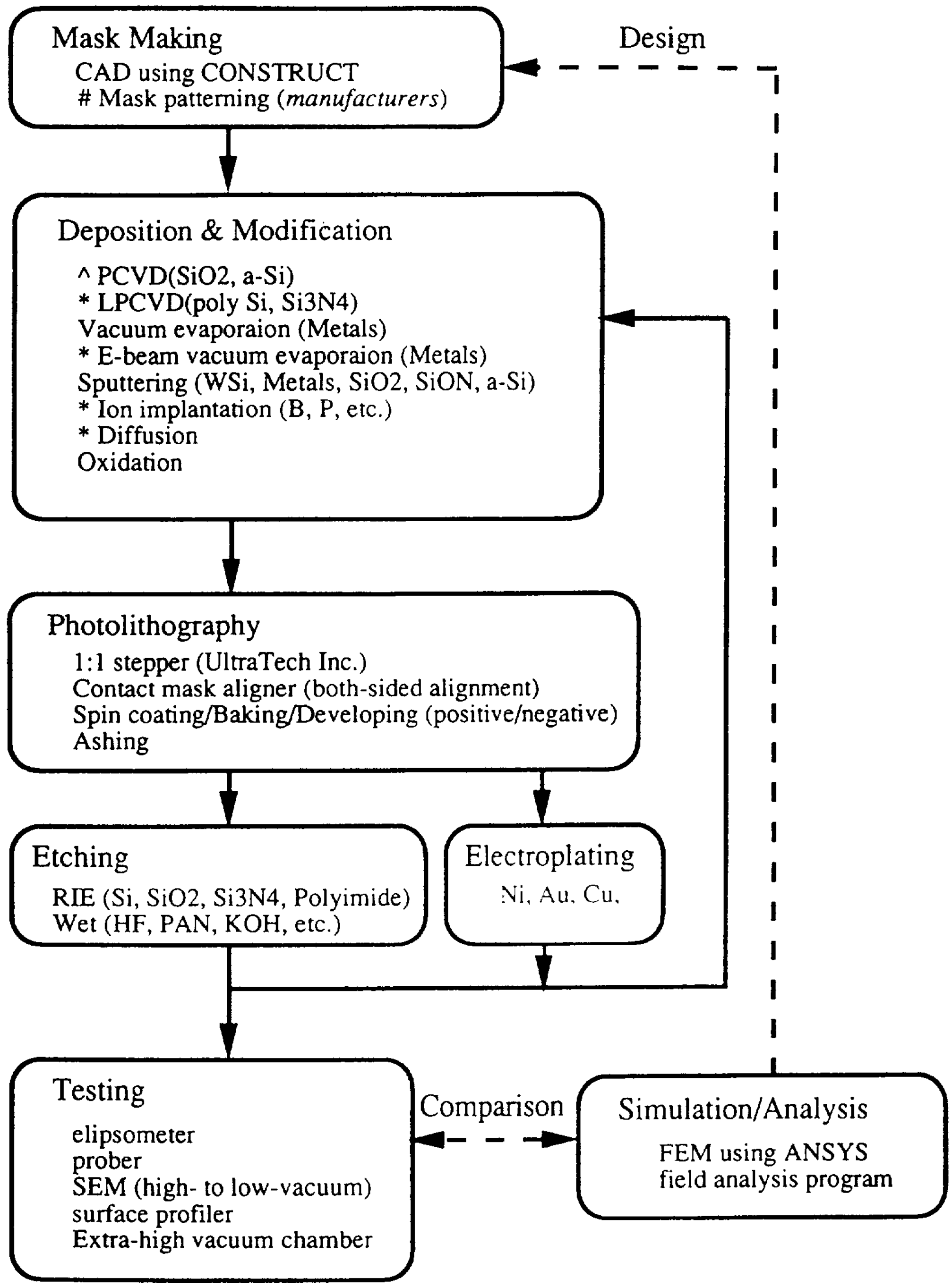


Figure IIS.1. Projects in H. Fujita laboratory, 1993.



this mark shows the process not available in Fujita Lab.
* this mark shows the process will be installed by Mar/94.
^ this mark shows the process is not used until safety regulation is cleared.

Figure IIS.2. Process facilities in H. Fujita laboratory, 1993.

QUESTIONNAIRE

Professor Kawakatsu's answers to the team questionnaire are keyed to the JTEC team's questions below. [A complete list of questions posed by the panel is included in the Yaskawa Tsukuba Research Laboratory site report, pp 225-236.]

B1. For which sensed variables and types of sensors will MEMS technology have the greatest importance? What are the key advantages of MEMS technology for these sensors?

B4. What new sensors can only be developed using MEMS technology? How does MEMS make these new sensors feasible?

In the field of scanning microscopy such as STM or AFM, the technique of probing samples with the probes in close proximity is expected to enable powerful measuring methods (e.g., differential tunneling), considered difficult in macrosystems.

B8. What are the principal problems in the use of scanning surface probes (e.g., tunneling current) as an approach to high-sensitivity sensor readout? Is this approach likely to find wide application?

As can be seen from the fact that the earlier models of atomic force microscopes using tunneling gaps for cantilever deflection detection [were] soon replaced by AFMs using other detection techniques, stability of tunneling tips and targets is not suited for built-in, on-chip sensors. However, a metal-insulator-metal structure using a suitable (if any) insulator layer may become a high sensitivity sensor with robustness against mechanical shock and contamination.

C2. Considering their importance to MEMS, in what order of importance would you place the following microactuation mechanisms: shape-memory alloys, electromagnetics, electrostatics, thermal bimorphs, piezoelectric bimorphs, piezoelectrics, electrostriction devices, [and] phase-change devices? How many of these do you expect will find commercial applications in high-volume products?

I am optimistic about the possibilities of the electromagnetic actuator. I think in some applications, it does not matter if the device for generating a field is large (e.g., a macrostator for levitation and attitude control of a microsuspended object).

F17. What are the principal barriers to the success of MEMS?

For commercial success: mass production of sensors in an easy to install package (e.g., a dual in-line package). For success in the frontiers of research, application of MEMS to fields where a macroscopic systems approach is not feasible.

Site: **The University of Tokyo**
Department of Mechano-Informatics
7-3-1 Hongo, Bunkyo-Ku
Tokyo 113, Japan

Date Visited: September 29, 1993

Report Author: L. Salmon

ATTENDEES

JTEC:

J. Giachino
B. Hocker
L. Salmon

HOST:

Hirobumi Miura Professor

NOTES

Professor Hirobumi Miura began by describing his previous work on macroscale robotics. He showed a film showing motion of macroscale biped and quadruped robots he had made. He also demonstrated a robot that completed the more complicated action of throwing a top. His goal was to make an intelligent robot, but he was disappointed with the results of his work. He had to use extensive external computer control to enable his robots to move. Although he used neural network and fuzzy logic control algorithms, the robots are still not intelligent.

The limitations caused by the control problems for his macrorobots led him to focus his attention on smaller robots that used physical properties of their construction to control motion. Professor Miura uses insects as models in his pursuit of simple control of robots. Insects such as the locust use the mechanical construction of their bodies to provide and control actuation. For example, Dr. Miura uses the locomotion mechanisms of insects as models for his microrobots. He showed us two types of microrobots: the microant and the micromosquito. Each of the microrobots uses a different physical mechanism for actuation.

The microant is actuated using the coupling of vibration from the base underneath the robot into its limbs. The base is vibrated at or near the resonant frequency of the microrobot. Direction of motion is determined through differences in the resonance frequencies of the limbs. Changes in the frequency of the table vibration then increase coupling into one limb or the other, and the microant turns. The micromosquito is made of a ferromagnetic material and is actuated by an external magnetic field. Professor Miura indicated that he believes that magnetic actuation is the most promising actuation approach for his microrobotic efforts. The limitation is the need for a large external magnetic field.

Several frequently used fabrication concepts are common to the microrobots described by Professor Miura. The microrobots have rigid, external structures based upon insect exoskeletons. Locomotion is based upon flexible hinges made by connecting rigid members with polyimide. Finally, all of the microrobots are assembled using an assembly process based on origami. The origami-like structure is evident in the microant shown in Figure Mechano.1. Another common theme of Professor Miura is to use milliscale robots to test out microrobot concepts. He showed us a millirobot constructed using shaped memory alloys that his students constructed to test out locomotion similar to that of an insect. Millisize models permit researchers to evaluate concepts without the complications introduced by microfabrication.

Professor Miura showed the JTEC team the laboratory used to fabricate and test microrobots. The laboratory contains the equipment needed to fabricate micromachines and utilizes clean fume hoods that serve a set of multiple processing tools. One hood has a spinner and a CVD system mounted into a common unit. The laboratory is not a clean room, but is sufficient to fabricate the simple structures Professor Miura is studying. Assembly and test equipment are also contained in the laboratory.

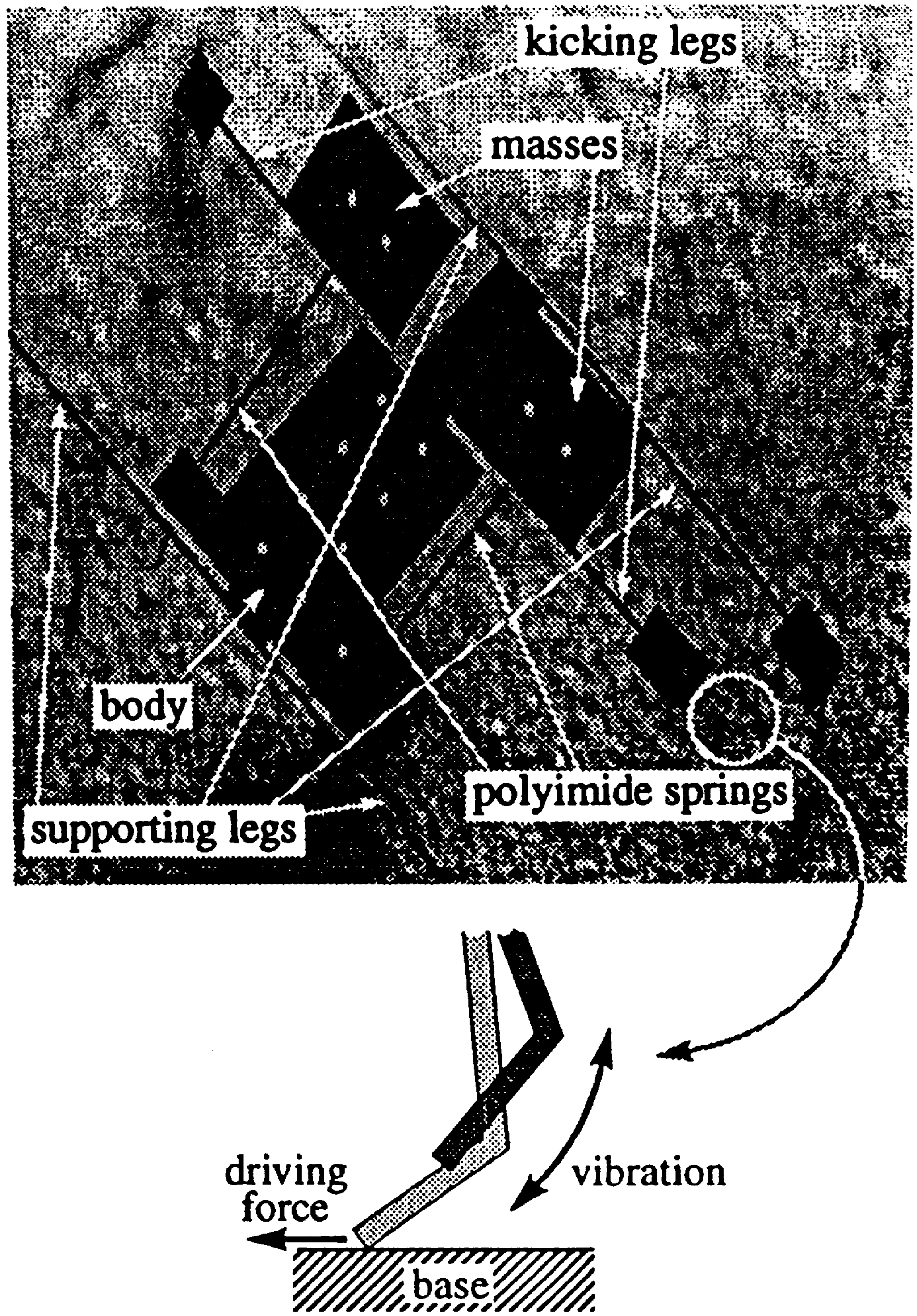


Figure Mechano.1. Origami-like structure evident in microant.

Site: **University of Tokyo**
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Tokyo 113, Japan

Date Visited: September 29, 1993

Report Author: J. Giachino

ATTENDEES

JTEC:

J. Giachino
G. Hocker
L. Salmon

HOST:

Naomasa Nakajima Director, Department of Mechanical Engineering for Production; Professor

RESEARCH AND DEVELOPMENT ACTIVITIES AND DISCUSSIONS

The JTEC team visited Professor Naomasa Nakajima in his office at the University of Tokyo. Professor Nakajima's laboratory is part of the Research Center for Advanced Science and Technology, which has 100 Ph.D. students, about 70 of whom are company employees. The company employees come to the university one to two days per week for classes. Most of these company students are managers or are at a higher level in their respective companies.

Professor Nakajima's Interdisciplinary Laboratory has seven graduate students from various companies. The laboratory uses many technologies to solve specific problems, with three to four students involved with micromachining.

The drive in the laboratory is to use many technologies to solve specific problems. The objectives of the laboratory are to take a higher level system view, to broaden the bases of technologies, and to diversify beyond just silicon. Professor Nakajima stated that the present state of micromachine technology is immature compared to the required level for commercial products (Nakajima 1993).

The work in his laboratory is driven toward medical applications. One area of work is a light driven micropump (Mizoguti et al. 1992). The target application for this device is in a catheter inside the body, where an optical drive for power is required for safety. The pump consists of an array of microcells, fabricated in silicon via wet chemistry, which have membranes that are actuated by light-heated working fluid. A new system uses an IR diode laser that can penetrate the silicon and eliminates the need for fiber-optic inserts into the cell. The pump can be operated at up to 20 Hz.

Another area of work in the laboratory is photoforming of fine parts (Takagi and Nakajima 1993). Extensive work has been done in developing materials for photoforming. The depth is controlled by using dyes to absorb the light and control the depth of penetration.

REFERENCES

Nakajima, N. 1993. "Challenge to New Artifacts: Micromachines." Paper presented at 1st International Symposium on Research into Artifacts.

Mizoguti, H., M. Ando, T. Mizuno, T. Takagi, and Nakajima, N. 1992. "Design and Fabrication of a Light Driven Micropump." *Proc. of MEMS.* Pp. 31-36.

Takagi, T., and N. Najakima. 1993. "Photoforming Applied to Fine Machining." *Proc. of MEMS.* Pp. 173-178.

Site:	**Yaskawa Tsukuba Research Laboratory** **5-9-10 Tokodai, Tsukuba** **Ibaraki 300-26, Japan**
Date Visited:	September 28, 1993
Report Author:	S. Jacobsen

ATTENDEES

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HOSTS:

Mr. Kabashima	Manager
Mr. Matsuzaki	Researcher
Mr. Matsuo	Researcher
Mr. Shimozono	Manager
Mr. Magariyama	Researcher
Mr. Mirua	Director
Mr. Mikuriya	Manager

NOTES

Yaskawa Tsukuba Research Laboratory was founded in 1915, and manufactures motorman robots, electric motors, inverters, controllers, and other products. The company now has sales of approximately $1,670 million per year. It currently has 4,500 employees, with 550 people in research and development departments. The laboratory has 15 people working on micromachines. Yaskawa's facilities are scattered throughout the country. The JTEC team visited the facility at Ibaraki.

Ibaraki's funding comes partly from government funds, but the laboratory spends three times the government amount from internal funds. The laboratory appears to have sufficient funding to support a large, qualified staff, and to maintain good equipment and buildings.

The basic research objective of the company appears to be a long-term focus on product development. The group that the team spoke with was not focused on products for near-term commercialization, but rather was operating in a very flexible way aimed at far horizons. The mix of projects at the facility seemed disjointed, giving the impression that despite their claim for focused development, they seemed willing to diversify the direction of their projects. It should be noted that Yaskawa is the lead group working on the "mother ship" portion of the national (MITI) micromachine program (see MITI/AIST and MMC site reports), and thus does direct a certain portion of its research towards the goals of this project.

Yaskawa representatives showed the JTEC team three project areas: bacterium flagella, robotics, and motors.

The bacterium flagella project is an experimental evaluation of propulsion by observing moving organisms in free swimming motion or with flagella bonded to a fixed substrate so that the body counter rotates. The group observed unwinding and redirected procedures of the bacterium, which some researchers think allow it to follow gradients in search of food, safety, and other desirable results. The Yaskawa group focused on defining actuation methods. Yaskawa and others postulate wall-located proton pumps that cause backflow of charged particles through biomotors to cause actuated rotational motion of the flagella.

The control of teleoperated robots project, with two arm-and-hand slaves and two arm-and-hand passive masters (no force reflection) were demonstrated. The hands included three fingers with multiaxis and spherically-shaped load sensors on each finger tip. System actuators were slow with limited force generation capability. However, problems of both stiction and backlash were substantial.

Viewing systems, including stereo cameras on slaves and magnetic head trackers on the operator, were shown but did not function successfully in peg-in-hole experiments.

The small motors project, where the JTEC team saw small magnetic motors 5 mm in diameter and small electrostatic motors of conventional design. The electrostatic motors were 13 mm in the outer diameter, 5 mm in rotor diameter, and generated a peak torque 10^{-6} N-m.

The motors were not micro but mini. There seems to be a question as to whether their motors could ever be manufactured for reasonable costs. No machining was used, but other less economic techniques were demonstrated. The motors consisted of metals and plastics and were fabricated using EDM, welding, drilling, and other approaches. While aware of micromethods such as silicon fusion and micromachining, the Yaskawa group did not seem to be using them.

The Yaskawa group was studying the crossover of advantages between electric and magnetic motors. For their designs, the group showed a crossover at 1.5 mm diameter rotor and a torque/volume of 2×10^{-8} N-m/mm^3.

QUESTIONNAIRE

A. Advanced Materials and Process Technology

1. What materials and fabrication techniques are most likely to be used in production for MEMS? Will MEMS continue to be based primarily on silicon IC technology?

Silicon that is expected to play an important role in the micromachine technology, is a superior material. It keeps on being the staple material. We use metals (e.g. aluminum, copper) and/or plastics for the insulator (e.g. epoxy resin, polyimide), ceramics, glass for micromachine's materials. Concerning the fabrication techniques, we use the conventional machining techniques, such as the wire electro discharge machining and machining by the machining center (drilling, cutting, grinding, and so on), and other machining. At the same time we use IC technologies, such as photolithography, deposition, etching, and so on.

2. What, in your opinion, is the most important new process or material needed for extending the capabilities of MEMS?

We think that the most important issue is the pursuit of the limit of conventional machining (such as mechanical machining, electro discharge machining and so on). Similarly, we think the fusion of new technologies (such as IC fabrication, thin film technology) and the conventional ones are important.

3. Are there plans to use X-ray lithography for micromechanics?

We have an interest in this technology, but don't plan to use it right now.

4. How attractive is the LIGA process for commercial use in MEMS at the present time? How attractive do you expect it to be in five years? Ten years?

We can't judge this technology now, since the cost and/or reliability for the parts of metallic mold has not been cleared. If they are supplied at a reasonable price, we want to use it for the very small parts such as micro gears and other mechanical parts. We expect it within the next five years.

5. If you are pursuing LIGA and LIGA-like high-aspect-ratio structures, what materials are being investigated and why? To what extent do you feel that structures produced using high-aspect etching will be competitive with those formed by plating?

The formation of an amorphous alloy has been under investigation (by Dr. Saotome, Gumma Univ.) using a characteristic of super plasticity. A stereolithography process has been investigating (by Dr. Nakajima, Tokyo Univ. and Dr. Ikuta, Kyushu Institute of Technology).

6. What are the prospects for a low-temperature wafer-scale bonding process for MEMS? How low in temperature can we go? Do you feel metal-metal, silicon-glass, or other interfaces are most promising?

We haven't studied bonding processes.

7. To what extent will silicon fusion play a role in MEMS? Is the area coverage sufficiently high? How much of a real problem is the high bonding temperature?

Silicon fusion will play an important role on MEMS based silicon technology. It is generally said that high bonding temperature will affect the mounted logic circuit. Our research activities have not reached to combine mechanics and electronics on the one chip.

8. What polymeric materials are being explored as photomasks for high-aspect-ratio structures? Is the use of conformal coating processes practical?

This item is not our field. We expect the advances in this field.

9. Polymers for thick photoresist applications are required by MEMS. Are Japanese photoresist suppliers responsive to this need?

We think that polymers for thick photoresist haven't been commercialized. We think Japanese photoresist suppliers are negative about developing new materials at present.

10. Do you feel that nested/stacked wafer-level microstructures based on multiple bonding and/or etch-back operations will be feasible within the next five years? Are they important for MEMS?

Stacked microstructures have advantages for precise assembly, and these will be feasible within the next five years.

11. It appears that precision injection molding could play a major role in MEMS. Would you comment on this, please.

Although this technology will need another precise assembly technique it will play a major role as a fabrication technique of micro parts.

12. Are room-temperature superconductors being explored, and if so, what materials and processing techniques are being used?

We think this item has no relation with MEMS. And this theme doesn't investigate in our company. Maybe, in Japan, many people are engaged in the research of this field.

13. Do you expect major advances in micromachining curing the coming decade? Will photo-assist etching or new etch-stops emerge to play a major role? What other technology additions do you consider promising?

We expect major advances in micromachining. Moreover we must drive forward ourselves.

14. What are the most important attributes you would insist on for a MEMS processing tool?

Mass productivity and ability [to make] real 3D microstructures.

B. Sensors and Sensing Microstructures

1. For which sensed variables and types of sensors will MEMS technology have the greatest importance? What are the key advantages of MEMS technology for these sensors?

From the view point of developing micro actuators, the rotational speed sensor, positioning sensor, electric current and voltage sensor have the important role. The advantage of MEMS is fusion and/or combination of sensors, electric circuits and actuators.

2. Approximately when will the new sensors under development today based on MEMS technology first appear in the market place?

Accelerat[ion] sensors, pressure sensors and flow meters [are] already [on] the market.

3. How can MEMS technology be used to improve existing sensors? What sensor types are likely to be improved the most?

We haven't participated in the development of sensors, so we don't have any comments.

4. What new sensors can only be developed using MEMS technology? How does MEMS make these new sensors feasible?

The answer is similar to No. 3

5. To what degree is self-testing likely to be possible with sensors? Will this be a major role for MEMS technology?

Self-testing will not be a major role, even if it will be [possible] to realize.

6. After pressures sensors and accelerometers, what is the next major sensor based on MEMS that will be mass-produced in high volume?

We don't have any comments.

7. To what degree are feedback readout schemes likely to be important in sensors? Will these feedback schemes involve MEMS?

We can't understand perfectly the meaning of this question.

8. What are the principal problems in the use of scanning surface probes (e.g. tunneling current) as an approach to high-sensitivity sensor readout? Is this approach likely to find wide application?

We are interested in these probes as peripheral technique region. But we don't have enough experiences for this region to comment.

C. Microactuators and Actuation Mechanisms

1. Can designs using arrays of microactuators achieve large and useful forces? Are there other devices similar to the large optical projection displays that have been reported that can be realized using MEMS technology?

Gathering arrays is one method to produce large force. One problem is how to control them simultaneously. We don't know the optical projection displays which are realized by MEMS.

2. Considering their importance to MEMS, in what order of importance would you place the following microactuation mechanisms: shape-memory alloys, electromagnetics, electrostatics, thermal bimorphs, piezoelectric bimorphs, piezoelectrics, electrostriction devices, [and] phase-change devices? How many of these do you expect will find commercial applications in high-volume products?

We are studying electromagnetic and electrostatic micro actuators. One reason is that these technologies are traditional ones of our company and the other reason is that these actuators are the most suitable actuators for the rotational motion. The selection of actuators must depend on the applications. So, the order of importance is case by case. We think at present the order from a viewpoint of volume, is as follows. First: electrostatics, second: electromagnetics, third: PZT and fourth: SMA.

3. What are the most reasonable candidates for prime movers for microactuation?

We think electrostatic actuators are.

4. To what extent can sticking problems due to surface forces be suppressed in microactuators? Will these problems seriously constrain the practical application of microactuators based on narrow gaps?

It will become a serious problem. Surface improvement and/or no mechanical contact techniques will be importance.

5. What is the most promising candidate for a microrelay? Where are such devices most likely to be used?

When it is necessary to move at high frequency range, electromagnetic and/or piezoelectrics are suitable. The other case, thin film SMA will be the candidate.

6. What are the main design issues in microfluidic systems? Where will such systems find their primary application?

This item is not our field. We don't have any comments.

7. What designs are most likely to be adopted for practical microvalves and micropumps? What is holding up the practical realization of these devices?

We think the type of membrane pump with electrostatic actuation is most practical. The bottlenecks for the practical use are reliability and life time.

D. Sensor-Circuit Integration and System Partitioning

1. Will MEMS technology lead to complete microminiature "instruments on a chip?" For what types of instruments?

There are many issues to realize "on the chip machine". Its application is now under investigation.

2. Will MEMS technology combine sensors and actuators into complete control systems? If so, what types of control systems will be most affected?

Yes, it will. About the specific types of control systems, we can't judge them.

3. Are systems involving sensors, actuators, and embedded microcontrollers likely to be realized in monolithic form or will they be hybrid? What factors are driving for monolithic integration for what types of products?

We don't have a clear answer concerning monolithic form. We think hybrid form is more practical than the monolithic one.

4. What levels of integration (transistor count) are we likely to see on MEMS chips by 1995? By the year 2000? Are full microprocessors needed or realistic?

We don't have any clear opinions. Full microprocessors will not be needed, since each device will have its own processor.

5. To what extent will embedded microcontrollers be used in (possibly hybrid) integrated sensing nodes -- high-end devices only, or will they eventually become pervasive in even low-end products?

First, these are used in high-end devices, after that these are expanded into low-end products.

6. What are the prospects for adopting sensor bus standards, at least in specific industries (automotive, process control, HVAC)? How important is the evolution of such standards to the development of MEMS?

In near future, the standards will have to be established on a worldwide scale. We think this is a very important issue.

7. Will sensor calibration continue to be done in hardware (laser-trimming or EPROM) or will it evolve to digital compensation in software? Is this an important issue in MEMS development?

Both techniques will be necessary. The final fine adjustment will be done by digital compensation in software.

8. Will a few standard processes emerge to dominate sensor-actuator-circuit integration or will widely divergent processes continue to be the norm in MEMS? What issues will determine the answer to this question?

The scale of the market is a dominant factor. But we don't exactly understand it's scale.

E. Advanced Packaging, Microassembly, and Testing Technology

1. What are the general directions for progress in packaging MEMS? What are the principal challenges here?

Our research [has not] arrived at the packaging stage. So, we don't have enough comment. Some techniques (such as bonding, assembling and precise positioning) should be investigated.

2. What will be the application and impact of MEMS on the packaging of sensors?

We have no comment.

3. How much of a problem is die separation for surface micromachined devices? Is this optimally performed after release?

We have no experiences with this technique. We don't have any comments.

4. How important are the chip-level packaging schemes now under development to MEMS devices and systems? Is the increased process complexity worth it?

The answer is similar to No. 3.

5. Are common packaging approaches across many types of devices feasible or will packaging continue to be very application specific?

The answer is similar to No. 3.

6. What viable techniques exist for coupling force from integrated microactuators while protecting the device from hostile environments? Can mechanical microactuators only be used inside hermetic packages?

The answer is similar to No. 3.

7. To what degree should MEMS continue to focus on monolithic silicon microstructures and to what degree do you think it is really better suited to milliscale integration with components combined using microassembly techniques?

The answer [to] this question depends on the application. In the medical application micro scale will be required and monolithic silicon microstructures will be suitable. On the other hand, in the industrial application the milliscale structures will be needed. In this scale the assembly technique will be suitable for making the structures.

8. Are there microassembly techniques that can be sufficiently automated to make millielectromechanical devices in high volume at moderate or low cost? What are the generic barriers to such devices and techniques?

We think the millielectromechanical system will act the major role, especially for the industrial use. Our main aim is the application of micromachines to these fields. We agree to the problems of assembly techniques have not been settled.

9. What techniques are available for testing MEMS structures after encapsulation/packaging? What happens when they are no longer viewable?

It is impossible to test after packaging. The only means to solve is to test every part at each process.

F. MEMS Design Techniques, Applications, and Infrastructure

1. The term "MEMS" has many meanings. Could you tell us your interpretation?

In general, MEMS means the system consists of the sensors, actuators and circuits based on silicon technology. We think MEMS and Micromachine have similar meaning. It means micro mechatronics system that consists of small parts (below mm size), and it will be made of various materials.

2. Is there a MEMS technology driver equivalent to the DRAM in the IC industry? If so, what is it?

We think it is sensor.

3. Is the integrated-circuit industry the principal application driver for MEMS? If so, what are the alternative drivers during the next decade, if any?

The industries [related to] the applications of MEMS will be the drivers (automotive, medical, etc.)

4. In what sensor application areas do you see MEMS technology having the greatest importance? (Examples might be: automotive, medical, robotics, consumer products, etc.) What are the key advantages of MEMS technology for these applications?

First, MEMS [will be] used for high-advanced [advantage?] technology such as automotive, medical and robotics. Gradually, it will be expanded to the consumer products. We don't know the key technology at present.

5. What will be the application and impact of MEMS on the interfacing of sensors to the environment?

We have no ideas.

6. Looking ahead five years, what new MEMS-based sensors and sensor applications do you anticipate?

Main products will be the accelerometers and pressure sensors. We expect progress [in] rotational sensors and positioning sensors.

7. In what time frame do you anticipate MEMS technology having the most impact on sensor products (for example, three years, five years, ten years, etc.).

Accelerometers and pressure sensors will be commercialized widely within three years. Compact sensors that detect rotational speed and position will be developed within five years.

8. What is the prognosis for MEMS foundries? Are they needed? What technologies would need to be present in a MEMS foundry?

MEMS is now [a] developing technology, so we don't have clear image for MEMS foundries.

9. What is the state of the art in MEMS reliability? Where are the principal problems?

MEMS [has not reached] the stage [where] we can discuss reliability. It will take us some time to reach [that] stage.

10. What is the "state of the art" in MEMS designability? How important are CAD tools for MEMS? Do you have an active CAD effort for MEMS in your organization?

We are trying to adopt CAE (CAD) technology for micromachine design in the fields of electromagnetic, electrostatic, thermal and mechanical analysis.

11. What priority would you place on the creation of a central MEMS database of material and design parameters? Does your organization have an active project in this area?

We don't have any concrete plan for [a] database system.

12. How much funding is being directed into MEMS research and development in your organization? What percentage is this amount of the total R&D budget?

We can't say the amount of the budget. Fifteen members have been connected with research [in] micromachines. (Yaskawa has 4500 employees and about 550 members are engaged in development and research activities.)

13. In your view, is enough funding available to support MEMS research in Japan? In the world? Are the principal bottlenecks to more rapid progress money or ideas?

We can't say we have enough fund[s] to install the expensive manufacturing equipment. We think the progress of MEMS depends on the idea.

14. What portion of your R&D funding for MEMS comes from internal, government or other sources? Has increased government funding had a major impact in your organization?

We participate in the MITI's ISTF program and are awarded grants for our research. But we spend twice or thrice as much as the money we receive.

15. What percentage of your research is directed toward specific products? Toward basic research?

Our research activities mainly consist of the development of the specific products. We have not been engaged in real basic research. In Tsukuba Lab., a few themes such as flagellar motor are directed toward basic research.

16. What emerging technologies do you see as having the largest influence on MEMS and why (i.e., LIGA, superconductors, submicron ICs, piezoelectrics, thin-film magnetics, etc.)?

The micromachine [field has] been very active, so new technologies will appear probably. But at present we don't know what [they are].

17. What are the principal barriers to the success of MEMS?

The key [to] the success of MEMS is whether we can find applications of MEMS which can't be realized without MEMS.

18. What do you believe to be the major competitive technology alternative to MEMS?

We don't know.

19. Are patents a key to commercial success or are base technology skills more critical?

Patents will be a key.

20. The first generation of university graduates who specialized in MEMS are now finishing their degrees. Are employment opportunities for these students plentiful in Japan?

Micromachine research will be continued in many Japanese companies. So, they have enough employment opportunities.

G. The R&D Process (if time is available after discussing technical issues)

1. What percentage of your research is being directed toward a specific problem -- looking at multiple solutions?

More than 90 percent of our research is directed toward a specific problem.

2. What percentage of your product is scheduled for captive use, and why did you choose to keep the product captive?

Fifty percent of our products [are] mechatronics products, and they are not scheduled for any captive uses. The other products [are] heavy electrical products and system products, [and] are scheduled for captive uses.

3. What percentage of your product is scheduled for end sale as a merchant item? Does it replace an existing product for your company or is it new?

We don't catch the meaning of this question.

4. What is the average time from research to market? From concept to research prototype, research prototype to engineering prototype, and from engineering prototype to market?

The development period is from one to five years. On the other hand, the research period is from three to ten years.

5. How do you determine whether to continue a project from research to development and to production? Who makes the decision to continue?

An inquiry committee, which consists of general managers of each division, determines whether the project should be continued or not.

6. How do you determine the potential products from a given technology? What processes are used?

We determine it using the help of our expert knowledge. We use the TQC technique and CE technique for comparison with the conventional technology and another company's technology.

7. Are you involved in joint development with other organizations? What kind (other companies, universities, foundations, etc.)?

We have many joint developments. These are the National project and some projects of Research Development Corporation of Japan, universities and KAST, etc.

7. How are the product goals established, and how are they converted to technical goals?

First we consider the goal of the sale, concerning the cost and market scale. So we develop the ideas which can realize these products using the help of our expert knowledge and the method of TQC.

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Date Visited: September 30, 1993

Report Author: K.D. Wise

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HOSTS:

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Dr. Hideto Iwaoka	General Manager, R&D Dept. 1, TERATEC Corp.
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NOTES

Dr. Hiro Yamasaki gave an overview of Yokogawa Electric Corporation, which is the largest manufacturer of measuring instruments in Japan and the Japanese equivalent of Hewlett Packard in the United States. Principal areas addressed by Yokogawa include measurement, control, and information, with annual sales of about $1.5 billion. Industrial automation systems (controls) make up about 85 percent of these sales, followed by test and measurement instruments, which comprise about 11 percent of sales, with 4 percent devoted to aerospace products. The annual expenditures on research are about 9 percent of sales. The company is about 10.6 percent foreign owned; in 1992 it employed about 6,880 people worldwide and had joint ventures with Hewlett Packard (in test/measurement), Johnson Controls (in industrial controls), and other U.S. companies. Work on MEMS is conducted under the industrial controls sector, which is very diversified. The largest application of

Yokogawa sensors was seen in the oil and petrochemical production area, although there was obvious interest in a wide range of other industrial control applications and in medical products. R&D activities address four principal areas: machines and electronics, electronics and optical measurements, information processing, and sensors and solid-state device technologies. A 400 M sample/s analog-to-digital converter, high-speed photodetectors, and a silicon resonant sensor were mentioned as examples of recent state-of-the-art products.

From the standpoint of application areas, Yokogawa is very well positioned to address the sensor area, and the corporation is very active in the area of programmable controllers for use in factory automation. This includes work on flat panel displays. Among the recent sensing instruments addressed are those for pH measurement, gas chromatography systems, a magnetic flowmeter, a pressure transmitter (smart pressure sensing module), a vortex flowmeter, and an instrument for measuring paper thickness/moisture in paper production.

Work on the photo-induced anodization of silicon for use in micromachining was next presented by Takashi Yoshida (1993). Conventional anodization of silicon is done under applied electrical bias in an appropriate solution containing hydrofluoric acid (HF). This requires contacts to all of the p-type regions on the chip that are to be anodized, which is often difficult or inconvenient to supply in a production situation. In this work, light is used instead, generating electron-hole pairs in the depletion regions surrounding the p-n junctions. The electrical contacts are thus eliminated. The anodized areas of porous silicon can be oxidized and then removed as desired with preferential etching. This has been used, for example, to form an n-type beam (microbridge) in a silicon substrate. The creation of the oxidized porous silicon areas, however, does create some stress problems due to material expansion, and these problems have prevented the use of this technique in devices such as the Yokogawa resonant pressure sensor. It does add another processing technique to the arsenal of available structures that can be created using micromachining, however, and may be useful in other areas.

Hideaki Yamagishi next presented a short description of the Yokogawa project under the MITI micromachine effort, which involves the use of focused ion beam (FIB) technology to realize an optical microspectrometer. The device is intended for an inspection module aimed at examining small, 1 centimeter in diameter cooling pipes in power-generation stations for buildup on the pipe walls. The device seeks to realize an optical sensor with a wide spectral range based on a tunneling device, a microantenna, and a variable optical filter with a very short optical path. The entire module is only 2.5 mm in diameter (Micromachine Center Staff 1992). A spiral antenna is photoengraved on a monolithic substrate. Radiation is launched from an optical source and bounced off of the inner surface of the pipe to be incident on the sensor. The voltage induced is used to induce tunneling across a very narrow gap of less than 10 nm. The use of FIB is essential in generating the small gaps. The ability to realize structures less than 50 nm in size has been demonstrated using point ion surfaces. The project appeared very innovative. The possibility of using X-ray lithography as an alternative to FIB was discussed; the high expense associated with the former was cited, along with the convenience and availability of FIB. The FIB may also be used in other related applications.

Gen Matsuno next described an odor sensor aimed at environmental monitoring. The device corresponds very closely to human odor sensitivity, and consists of a resonator coated with a membrane selective to specific molecular absorption. The stability and reproducibility of the device are still being studied. There was discussion of the possibility of realizing a microgas chromatograph at this point. Such a structure had clearly been carefully considered; however, Yokogawa felt that such a device would need a leak-free microvalve, and that the microvalve and the column were the key issues.

Dr. Hideto Iwaoka next described work on advances in compound semiconductor lasers and optical waveguides under way at the Optical Measurement Technology Development Company, a joint effort with the Japan Key Technology Center. Significant advances have been made with distributed feedback semiconductor laser structures (Hirata et al. 1990) and monolithically integrated waveguides by compositional disordering (IWD) lasers (Hirata et al. 1991). This appeared to be very good work, but did not appear to be closely related to MEMS.

Yokogawa produces two pressure sensors: an older piezoresistive pressure sensor and a more recent resonant device aimed at high-performance applications and DPharp. The latter device was described at the 1988 Japanese Sensor Symposium (Ikeda et al. 1988) and at the 1989 International Conference on Solid-State Sensors and Actuators (Ikeda et al. 1989), where it received considerable attention. It is a high-performance device produced by a very challenging process involving the use of four sequential selective-epitaxial growth steps to produce an electromagnetically-driven resonant beam in a batch vacuum-sealed (<1Pa) cavity. The beam is formed in a diaphragm and is subjected to stress as the diaphragm flexes in response to differential pressure (DP), causing the beam to alter its natural frequency. Two beams are actually used differentially so that the actual output is the difference in two frequencies. The present DPharp does not have on-chip circuitry and is produced in the facility at Yokogawa headquarters. It is an excellent device for high-precision measurement applications, but due to the associated process complexity was not viewed as likely to replace conventional diaphragm devices at the lower end of the performance scale. The DPharp can be realized to cover differential pressure ranges from 1 kPa to 14 MPa (full scale) by varying the diaphragm thickness. Accuracy is achievable to ±0.1 percent over a span of about 40:1 (Ikeda 1992). Typically it is closer to ±0.01 percent according to data in Saigusa et al. (1992).

There has been considerable work at Yokogawa on smart sensing modules (pressure transmitters) based on this transducer (Ikeda 1992; Saigusa et al. 1992).

These transmitters consist of a differential pressure sensor capsule that couples to the sensor chip and its associated drive/detection circuitry. This assembly drives a microprocessor, which carries out linearization, temperature compensation, self-diagnostics, and communication with the outside world. EPROMs store sensor parameters to enable compensation. Output format is currently a 4-20 mA current loop. The overall assembly is complex, especially from the standpoint of its mechanical/packaging aspects. This general approach to the realization of a smart sensing node is very much in line with approaches currently being developed in the United States, however. The drive/readout electronics for the sensor is implemented in a multichip hybrid configuration and has not been merged monolithically with the transducer at this point.

REFERENCES

Hirata, T., M. Maeda, M. Suehiro, and H. Hosomatsu. 1990. "GaAs/AlGaAs BRIN-SCH-SQW DBR Laser Diodes with Passive Waveguides Integrated by Compositional Disordering of the Quantum Well Using Ion Implantation." *Japan Journal of Appl. Phys.* 29, June: L961-L963.

Hirata, T., M. Maeda, M. Suehiro, and H. Hosomatsu. 1991. "Fabrication and Characteristics of GaAs-AlGaAs Tunable Laser Diodes with DBR and Phase-Control Sections Integrated by Compositional Disordering of a Quantum Well." *IEEE J. Quantum Electron.* 27, June: 1609-1615.

Ikeda, K., et al. 1988. "Silicon Pressure Sensor with Resonant Strain Gauge Built into Diaphragm." *Technical Digest of the 7th Sensor Symposium.* Pp. 55-58.

Ikeda, K., et al. 1989. "Silicon Pressure Sensor Integrates Resonant Strain Gauge on Diaphragm." *Digest 5th Int. Conf. on Solid-State Sensors and Actuators.* June: 146-150.

Ikeda, K. 1992. "Applications of Micromachining for Resonant Pressure Sensors." (Obtained at Yokogawa).

Micromachine Center Staff. 1992. *Micromachine: Introduction to the Micromachine Center.* (Booklet).

Saigusa, T., H. Kuwayama, S. Gotoh, and M. Yamagata. 1992. "DPharp Series Electronic Differential Pressure Transmitters." Tokogawa Technical Report (English Edition). No. 15. Pp. 30-37.

Yoshida, T., T. Kudo, and K. Ikeda. 1993. "Photo-Induced Preferential Anodization for Micromachining." *Sensors and Materials.* 4: 229-238.

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ATTENDEES

JTEC:

H. Guckel

HOSTS:

Dinesh K. Sood	Professor
Dr. Ronald B. Zmood	Principal Lecturer, Dept. of Electrical Engineering
Dr. M.J. Murray	Chief, Material Sci. & Technology Div., CSIRO

NOTES

The Royal Melbourne Institute of Technology (RMIT) is involved in significant activity in micromechanics, specializing in magnetics, which is not surprising since Dr. Ronald B. Zmood has contributed significantly to magnetic bearing issues in larger machines. Experimental and theoretical considerations of magnetic actuators are in progress. A major concern at RMIT is magnetic bearings and their control systems. The experimental work involves small wound coils and electroplated planar coils via photoresist pattern definition.

The actuator work is supported by a strong effort in material sciences that contributes to fabrication techniques and material science topics for magnetic materials. At RMIT this work is organized via the Microelectronics and Materials Technology Centre, which facilitates interdisciplinary activities and allows, for instance, for the strong cooperation between Professor Dinesh Sood and Dr. Zmood. These two senior members are supported by several graduate and undergraduate students in micromechanics.

Professor Sood arranged a meeting with Dr. M.J. Murray, Chief of the Material Science and Technology Division, CSIRO. This very large national laboratory division has an Australian government budget of $A 10.5 million annually that it augments with external grants of up to $A 15.6 million. The division responds to industrial Australian needs and has recently spun off a company, Ceramic Fuel Cells, Ltd., which produces solid oxide fuel cells. The division has a large, highly-skilled research staff with state-of-the-art research equipment and research topics. A joint effort between RMIT and CSIRO in micromechanics appeared to be in the consideration phase.

The relationships between the Australian micromechanics effort and the Japanese effort are based on Japanese funding at RMIT. Discussions at the Micromachine Center at Tokyo indicated that the only non-Japanese university that received funding through MITI/NEDO is RMIT. The funding level in Australia is significant enough to make it the main financial support in micromechanics at RMIT. Senior staff at RMIT are apparently pleased with the financial support. They explained that they had resolved the patent issue by protecting prior intellectual properties to the satisfaction of both groups. Patent issues based on current research have also been resolved and did not produce the hurdle that some American universities perceived them to be when approached by MITI. It was felt that the ownership and benefit formulas provided in the final agreement were equitable to all parties. Perhaps the only mildly negative comments in Australia involved frequent reporting requirements with executive summaries in Japanese and very strict fiscal accounting.

Professors Sood and Zmood and Dr. M.J. Murray made this visit not only a learning experience but also a very pleasurable one.

APPENDIX D. THE DEVELOPMENT OF MICROELECTROMECHANICAL SYSTEMS: Activities in the United States of America

1. INTRODUCTION

This appendix is a brief review of the development of microelectromechanical systems in the United States. It was prepared by this JTEC panel as a baseline against which to compare Japanese activities in this area. Indeed, this appendix will review the recent approaches taken in the United States, and U.S. perceptions of the challenges that confront the continued growth of this area, as a basis for understanding the approaches taken in Japan and the important role that organizations there have played and continue to play in this field. The views expressed here necessarily represent those of the panel members alone, but are nonetheless thought to accurately reflect the current situation in the United States in both academia and industry.

The field of MEMS has been recognized internationally only within the last few years, although it is rooted in efforts on sensors and actuators that go back thirty years or more. The field has been driven by the rapid global progress in the field of microelectronics, where solid-state microprocessors and memory have revolutionized many aspects of instrumentation and control, and have facilitated explosive growth in data processing and communications for three decades. Many of the emerging application areas for microelectronics, however, deal with nonelectronic host systems and thus require that parameters such as pressure or flow be converted to electrical signals that can be processed by computer. After the necessary control decisions are made electronically, the resulting electronic signals can be fed to actuators to control the parameters of the host system. Figure D.1 shows the general arrangement of this control loop. The peripheral functions of sensing and actuation represent the principal bottlenecks today in the application of microelectronics to such systems, including those in automotive areas (both vehicular and smart highways), environmental control (HVAC), global environmental monitoring, health care (monitoring, diagnostics, and instruments for microsurgery and prosthetics), defense, automated manufacturing (including those for use in the microelectronics industry itself), and important consumer products. It is thus evident that sensors, actuators, and MEMS are likely to exert considerable leverage on the microelectronics industry beyond the considerable direct markets for them, since they will enable the use of microprocessors and memory that otherwise could not be applied.

During the past thirty years, considerable strides have been made in the realization of sensors and actuators using solid-state technology, and most efforts have come to concentrate on this approach (Petersen 1982). Beginning with visible image sensors in the mid-sixties and then pressure sensors in the 1970s, most efforts to realize sensors have drawn extensively from integrated circuit technology and have been silicon-based. In the 1980s, accelerometers emerged as additional high-volume product targets, driven primarily by needs in the automotive industry. Both microactuators and MEMS were born during this decade. Today, visible image sensors are approaching the resolution of photographic film (Nomoto 1993) and offer the promise of automatic electronic processing of both video and still images. Infrared imaging has similarly resulted in large area arrays, and more recently has been demonstrated in several uncooled implementations based on micromachining (Wood, Han, and Kruse 1992). Solid-state pressure sensors have been demonstrated over a broad range of applications, from ultrasensitive devices capable of serving as solid-state microphones (Kim, Kim, and Muller 1991) or capacitive manometers (Cho and Wise 1993) to rugged devices used in electronic transmissions and in the hydraulic control of heavy equipment, spanning at least eight orders of magnitude in pressure. A variety of accelerometers are being merged with on-chip circuitry for high-volume applications (Payne and Dinsmore 1991), and inertial navigation systems based on integrated gyroscopes (Bernstein et al. 1993) are in development in a number of companies. Microflowmeters are emerging for industrial process applications, and still other devices are being designed for chemical sensing and for applications in decoding the human genome. Many of these emerging applications are potentially very high in volume and very important to global society.

From the perspective of this particular study, it is important to define what we mean by MEMS, since there is as yet no clear definition of this term. It clearly includes many sensors and actuators, but by no means all of them. For purposes of this report, "MEMS" are batch-fabricated devices that involve the conversion of physical parameters to or from electrical signals and that depend on mechanical structures or parameters in important ways for their operation. Thus, this definition includes batch-fabricated monolithic devices such as microaccelerometers, pressure sensors, microvalves, and gyroscopes fabricated by micromachining or similar processes. Also included are microassembled structures based on batch-fabricated parts, especially when batch assembly operations are used, but this study will not focus on individually-fabricated devices that are unlikely to see wide use. It is expected that an interface to electronic signal processing will exist in most MEMS, which implies that they will include sensors, actuators, or (in most cases) both. Image sensors, chemical sensors, and purely thermal or magnetic devices, however, will not be covered in detail in this study even though they may involve technology and generic microstructures that are similar to those used in MEMS. New materials and processes such as LIGA, however, are an important part of the study along with testing, packaging, and many issues associated with the design and development infrastructures needed for MEMS.

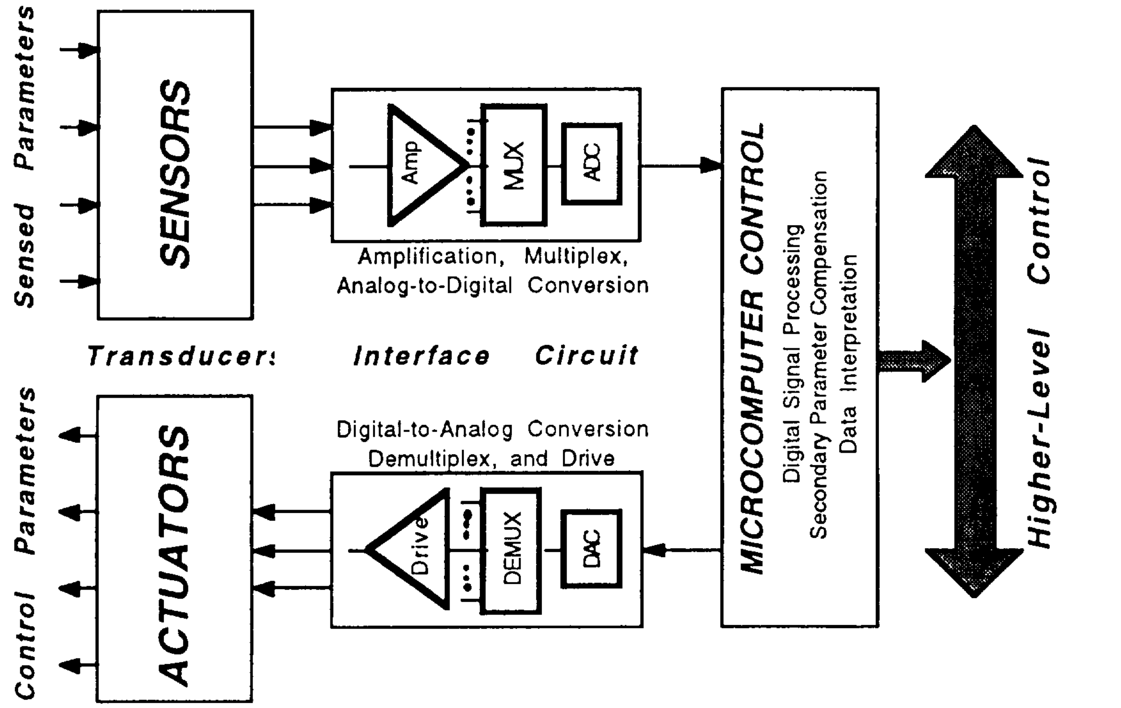

Figure D.1. Structure of a sensor/actuator control loop typical of evolving microelectromechanical systems.

Figure D.2 summarizes many of the sensor development activities in the United States since their beginnings in the 1950s in materials-oriented research at Bell Telephone Laboratories, Honeywell, and Westinghouse. As part of the development of beam-lead (air-isolated) integrated circuits at Bell Telephone Laboratories in the 1960s, precision silicon etching technology was developed, and by the mid-seventies this had been utilized in important ways by the sensor community and had been rechristened "micromachining." The earliest university work in this area was probably that started at Stanford University in the mid-sixties, followed by important efforts at Case Western Reserve University, the University of California (Berkeley), the University of Wisconsin, Massachusetts Institute of Technology, the University of Michigan, the University of Utah, and elsewhere. Indeed, the development of sensors in the United States was pioneered primarily in academia, with commercialization efforts relatively slow in coming. The field was enhanced significantly with the development of surface micromachining at the University of California (Berkeley) and the University of Wisconsin in the mid-eighties, which made possible a wide array of additional microstructures that could be realized using silicon technology. Many of these new devices were microactuators, and the concept of marrying sensors, actuators, and electronics to collapse entire microinstrumentation systems to the level of a single chip emerged as a result. It was in the late 1980s that the term "MEMS" was born to describe one portion of the expanding sensor-actuator area.

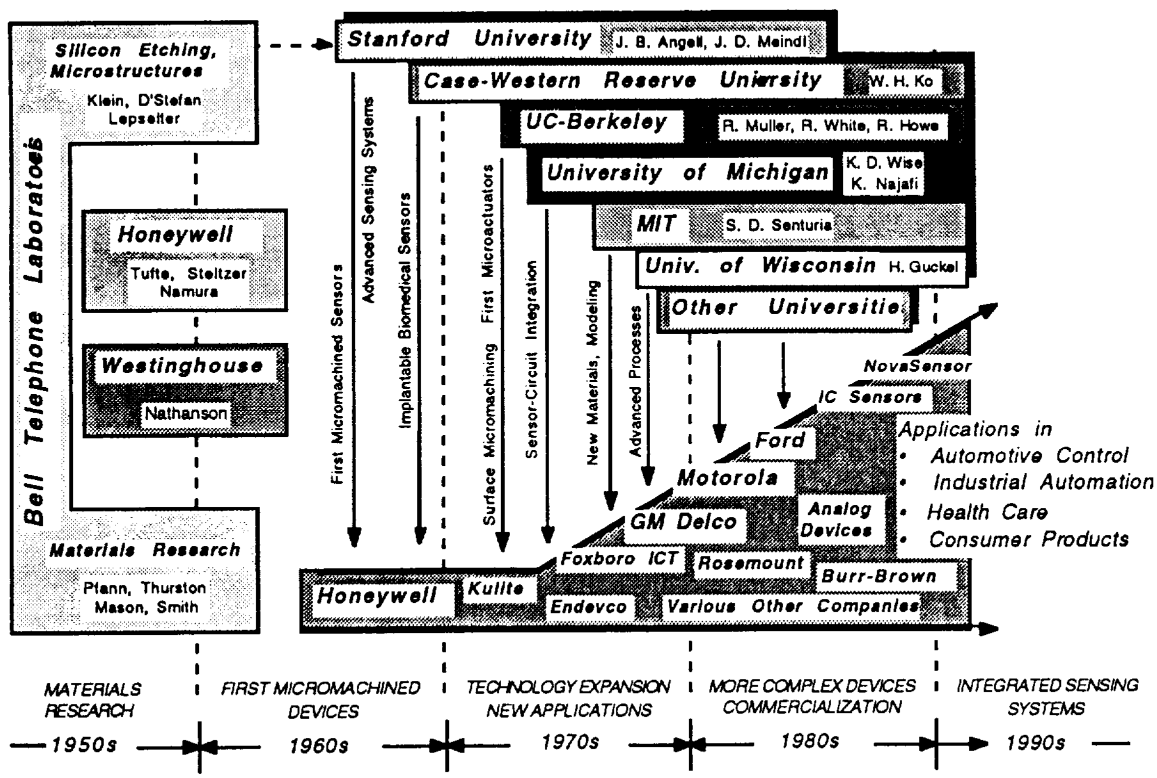

Figure D.2. The development of solid-state sensors, actuators, and MEMS in the United States.

The 1980s saw the demonstration of many new devices in prototype and increasing efforts at commercialization. With the establishment of many international and regional conferences during the 1980s, solid-state sensors and actuators emerged as a recognized and important field, centered in microelectronics but extending broadly into mechanical engineering, robotics, and a variety of additional fields as well. It appears that the decade of the nineties will be devoted to merging devices and control electronics to form integrated microsystems, implemented in either hybrid or monolithic form, and to applying these microsystems to meet a number of application needs.

While increasingly recognized as important in the implementation of a wide variety of emerging systems, however, enthusiasm over the realization of sensors, actuators, and MEMS using microelectronic technology must be tempered by the realization that many such devices have existed in various forms for a long time. The commercialization of these devices has been slow, and in many areas technology push has been considerably stronger than market pull. In some cases, the control system hierarchy into which these devices must work must change considerably in order to accommodate them, and the general lack of synergy between the sensing and control areas has undoubtedly retarded progress. Simply replacing earlier devices with solid-state versions of them has not fulfilled the potential of this area, and going beyond simple component replacement into integrated microsystems has required interdisciplinary cooperation that has been difficult to achieve, at least in the United States. Has the technology associated with MEMS really matured to the point where high-volume devices can be realized using batch processes with high yields? If not, when will it do so? Can the specialized processes required for the realization of microelectromechanical microstructures really be successfully merged with circuit processes to form microsystems on a chip? Is this necessary, or will hybrid systems do just as well? Where are the markets for these devices that will demand continuous technology improvements similar to what the memory has done for microelectronics? Where are the high-volume markets that will fuel the sensor/actuator/MEMS industry and significantly benefit society? These are some of the questions to be considered in this study. They are being addressed on a global scale with an increasing sense of urgency.

In order to answer such questions, funding for MEMS research has increased substantially on a worldwide basis over the past decade. Funding for MEMS in the United States began with early efforts funded by the mission-oriented agencies of the federal government, especially the National Institutes of Health and the National Science Foundation (NSF). In the late eighties, efforts intensified with a very visible program run at NSF under their Emerging Technologies Initiative. This was the forerunner of support by the Advanced Research Projects Agency, which has further enhanced funding in this area. While the total funding for MEMS and MEMS-related activities in the United States is not known, university funding is probably no more than $20 million per year. The effort in Europe is felt to be somewhat larger. The Japanese effort under MITI has been the most visible effort globally, and yet how much of this effort is directed specifically at MEMS and how MEMS is interpreted under this program has not been entirely clear. Japanese programs have been significant in the development of sensors, actuators, and MEMS through programs at a number of universities and companies, and the leadership of Japanese industry in consumer products puts them in an excellent position to benefit from MEMS technology.

Microelectromechanical systems have the potential to leverage microelectronics into important additional areas that could be revolutionized by low-cost electronic signal processing, computing, and control. These microsystems could have a profound effect on society, but will require a synergism among many different disciplines that may be slow in coming. Global leadership and cooperation will be absolutely required if the benefits of MEMS are to be realized in a timely way. Only understanding the potential of this emerging field and working together to overcome its challenges will ensure the early utilization of MEMS to benefit mankind.

2. U.S. EFFORTS IN ADVANCED MATERIALS AND PROCESSES (Henry Guckel)

Micromechanics uses construction tools that fall into three loose categories: bulk machining, surface machining, and processing sequences that are neither bulk nor surface machining procedures. Bulk micromachining, which typically uses single crystal material with orientation and dopant-controlled etches, is the oldest micromechanical processing tool. This technology, when coupled with wafer-to-wafer bonding and wafer thinning techniques, has produced economic successes in the United States, as illustrated by Lucas NovaSensor, Inc., and the company's many products that use this technology. Research in both this processing tool and its applications continues in the United States, and is exemplified by the efforts and progress that Professor M. Schmidt of MIT has demonstrated (Parameswaran et al. 1993; Huff, Gilbert, and Schmidt 1993).

Surface micromachining is dominated by low-pressure chemical vapor deposited polysilicon and silicon nitride films with variable compositions. Deposition techniques are now sufficiently refined to allow production of films with adequate mechanical performance at many U.S. facilities. This situation has been taken advantage of by a foundry approach to micromechanics. The MCNC Electronic Technologies Division now offers a double-layer polysilicon process to the U.S. micromechanics community with user-defined geometries. A second indication of maturity in surface micromachining involves Analog Devices, Inc. This company has integrated a surface-micromachined accelerometer with electronics for automotive applications.

Difficulties in surface micromachining persist in undesired surface adhesion during processing for mechanically weak structures such as large area diaphragms. Some of these problems have been solved by using freeze-sublimation cycles based on cyclohexane, as demonstrated by the University of Wisconsin Micromechanics Group (U.S. Patent 1991). A very elegant solution has been reported by R.T. Howe and associates at the University of California at Berkeley (Mulhern, Sloane, and Howe 1993). They use liquid CO_2 at 25°C and 1,200 psi as their starting ambient and form a supercritical fluid at 35°C, which exits in gaseous form. Both processes avoid surface tension-induced deflections and lead to free-standing structures.

On the positive side in surface micromachining is the increasing confidence in polysilicon as a mechanical construction material. Long-term test data for 500 kHz clamped-clamped beam resonators has been reported (Guckel et al. 1993d), and indicates that material-induced drift is less than 1 ppm/month with quality factors above 100,000. These results point at excellent future sensors with direct optical to mechanical interfaces.

A very elaborate set of processing procedures that employ surface micromachining in various forms has been developed at Cornell University by Professor N.C. MacDonald's group (MacDonald 1993). The work is motivated by the interest that the Cornell group has in tunneling structures. The Cornell process has progressed from simple tunneling tips to triple-tip structures to multiple tips on moveable surface-micromachined three-axis actuators.

Very encouraging efforts in surface micromachining that use metal films instead of polysilicon as a construction material are the digital micromirror devices that Texas Instruments, Inc., is fabricating (Sampsell 1993b). These devices have been produced in array form with sizes to 768 x 576 pixels. The mechanical structure is that of a torsional mirror that is driven by a static random access memory cell (SRAM) circuit. The entire mirror array can therefore be addressed on a pixel-by-pixel basis and forms a high definition display system.

There are several efforts in the United States that do not fall into the traditional micromechanics construction tool categories. These programs deal with at least two major issues: thick photoresist processing and special processes for packaging.

In the United States, thick photoresist processing has been pursued from two perspectives: optical exposure and LIGA-like X-ray exposures. The two approaches differ in their intent: modest photoresist thicknesses of a few hundred microns, and very large height processing of several millimeters. The first category, optically-defined thick photoresist processing, is exemplified by the work of Professor M.G. Allen, Georgia Institute of Technology, who uses spin-coated, light-sensitive polyimide as the photoresist of choice (Allen 1993). The chemical stability of the polyimide is exploited by applying it over a plating base and filling the recesses via electroplating. Ferromagnetic metals have been used in this work to produce magnetic micromechanical devices.

The Micromechanics Group at the University of Wisconsin-Madison has pursued LIGA-like processing for some time. The group's photoresist of choice is polymethyl methacrylate (PMMA), which the group's mechanical engineers apply by casting and in situ polymerization with varying degrees of cross-linking. This procedure, which was first used in Germany, can produce acceptable results to 500 μm or so, and in fact has been used in Madison to produce devices with heights to 700 μm. Larger thicknesses are limited by photoresist strain, which is a consequence of this processing procedure. This difficulty has recently been overcome by using cell-casted annealed sheets of PMMA and solvent bonding them to the substrate (Guckel et al. 1993c). Figure D.3 illustrates the result. The thickness of the PMMA layer may be adjusted by mechanical machining. The process may be used for other photoresist and can produce strain-free photopolymer layers of arbitrary thickness. The technique has been used to produce LIGA-like structures with heights above 1 mm.

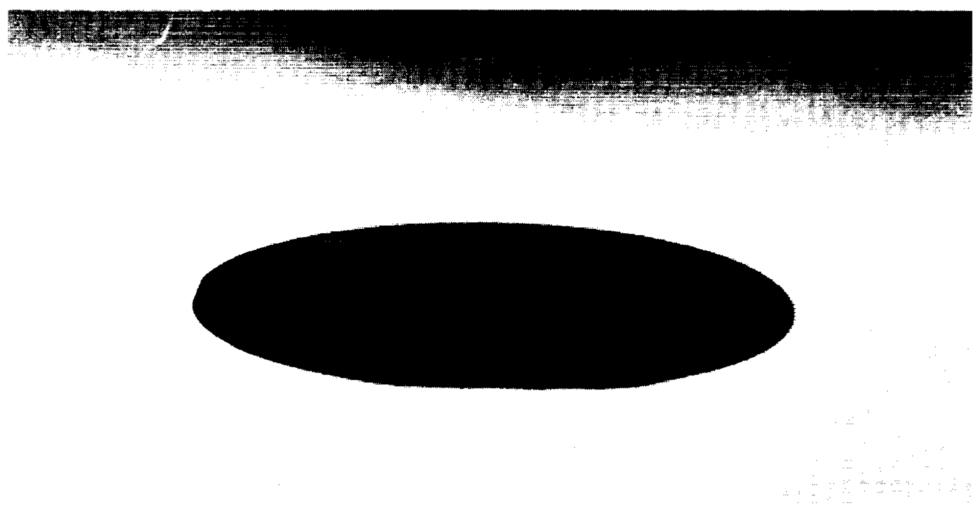

Figure D.3. Three-inch silicon wafer with two-inch PMMA photoresist layer of 3.2 mm thickness.

Thick photoresist processes can be exploited by additive processing, which fills the photoresist recesses. This is typically (but not always) done by electroplating. Research in this area has centered on two major problems: plating into small geometries with large heights, and repeatable properties of deposited metals and alloys. Of particular significance are magnetic properties because this type of technology lends itself to electromagnetic device construction. The fabrication of 78% Ni, 22% Fe alloys with permeabilities of 10,000 or so, and saturation flux densities of 1.0 Tesla is noteworthy and fills the need for a soft magnetic material (Guckel et al. 1993a). Materials that can be used for permanent magnets are also of concern. However, these are more difficult to process and progress is slower.

Magnetics offers many device possibilities. Emphasis at Wisconsin has been on magnetic micromotors and, in particular, machines with low friction via magnetic levitation for rotational speeds above 1 x 10^6 rpm. Figure D.4 indicates recent results.

Packaging of micromechanical devices forms a major challenge to fabrication tools. Normally these problems are left to commercial laboratories. An exception is the work of Professor K. Najafi, University of Michigan, who works on biomedical devices that must be packaged for functional testing (Ziaie et al. 1993). His recently reported hermetic packaging technology with feedthroughs demonstrates that micromechanics can be used to contribute to the solution of highly complex packaging problems.

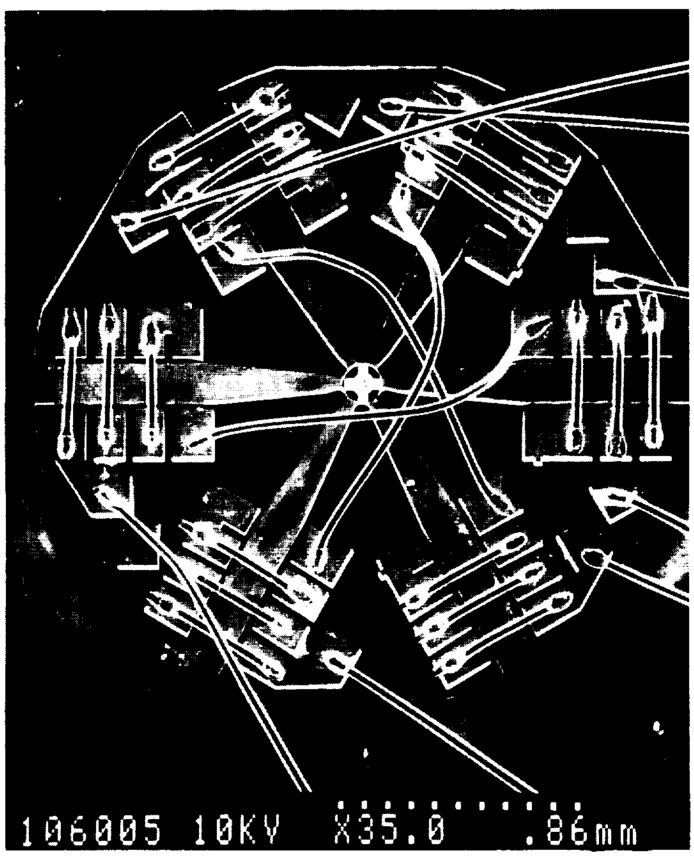

Figure D.4. A planar magnetic micromotor with rotor diameter of 150 μm and a central shaft diameter of 35 μm. The construction material is 78% Ni, 22% Fe permalloy. The machine has been operated to 55,000 rpm.

3. SENSORS AND SENSING MICROSTRUCTURES (G. Benjamin Hocker)

Micromachining technology began to develop rapidly over fifteen years ago, using the materials and processes developed for the integrated circuit industry to form miniature structures in silicon and related materials for purposes other than electronic devices. The fabrication of miniature solid state sensors has always been the main thrust of micromachining technology. What is today called MEMS is in most ways only an evolution and expansion of this technology thrust. The improvements possible today with MEMS technology involve the expanded range of materials and processes that can be employed, and the precise dimensional scale and the mechanical complexity that can be achieved in devices. Sensors are still the major application thrust of MEMS, particularly in commercial products.

As the term "microelectromechanical systems" suggests, MEMS technology relates most directly and has the greatest impact on sensors for mechanical variables. It must be noted that, because of the evolutionary development of micromachining technology for sensors, it is often not possible to specify that certain mechanical sensors employ MEMS while others do not. In contrast, most of the solid-state sensor developments for chemical sensors, gas sensors, and biosensors do not employ MEMS concepts and technology and are not discussed here.

There are major MEMS sensor efforts in the United States focusing on the development of advanced silicon pressure sensors and silicon accelerometers. These efforts are primarily driven by existing and potential high-volume applications in automotive, medical, and consumer products. The most important requirements are typically for moderate performance at very low cost. The batch-fabricated nature of MEMS sensors addresses these needs. Other advantages of MEMS sensors for many applications include small size and low power. Development work is under way in industry as well as at many universities. Development efforts also address high-performance needs in military and industrial systems. Some advanced pressure sensors and accelerometers are commercially available, while others may be expected in the marketplace in the next three to five years.

While silicon diaphragm pressure sensors have been commonplace for many years, more recent developments in the United States resulting from MEMS technology are resulting in significantly smaller and potentially less expensive devices. These devices are most suitable for low to moderate performance applications where cost and perhaps size are critical, such as disposable medical sensors and consumer products. One technique developed at the University of Wisconsin (Guckel et al. 1987) uses thin film polysilicon for the sensor diaphragm. Because the polysilicon diaphragm is only about one-tenth the thickness of conventional silicon pressure sensor diaphragms, the polysilicon devices are correspondingly smaller. Thus, there are many times more sensor die per wafer, and the cost is much lower. Another technique originated by NovaSensor (Petersen et al. 1988) employs high-temperature fusion bonding of silicon wafers to form inward tapering cavities under single-crystal silicon diaphragms. This technique can also result in much smaller sensor die than standard techniques. As a result, these devices are being used in medical catheters where both size and cost are critical.

Many pressure sensing applications may require measurement of low pressures in the range of 1,000 Pa, but adequate sensitivity to such low pressure is not easily accomplished with conventional silicon diaphragm sensors. However, by using advanced MEMS micromachining technology to add corrugations or bosses to the diaphragm, areas of stress concentration can be formed that facilitate these low-pressure measurements (Mallon et al. 1990). Several such low-pressure micromachined sensors are commercially available.

Technology for miniature resonant strain sensors has been demonstrated (Guckel et al. 1992; Petersen et al. 1991) that may replace capacitive or piezoresistive readout of silicon diaphragm pressure sensors for improved performance. These devices employ a miniature beam driven into mechanical resonance by feedback electronics. The resonant frequency is a sensitive measure of strain, but is relatively insensitive to temperature or to the electrical properties of the device. The devices are located on a conventional silicon pressure sensor diaphragm, where they function as frequency output strain gauges. There are no critical analog gain stages, and the frequency output can be easily interfaced to digital signal processing circuitry. A vacuum shell can be integrally formed around the beam to allow operation in any media. The mechanical complexity and very small size required for these devices is made possible only by advances in MEMS technology.

Because of the large potential markets in automotive applications for sensors for air bag deployment and active suspensions, there are many efforts under way in the United States to develop miniature silicon accelerometers. MEMS technology is key to achieving the required performance combined with the low sensor costs demanded by these applications. Several accelerometers using bulk silicon micromachining to form a single-crystal silicon proof mass and supporting flexures have been developed (Bart et al. 1988; Terry 1988) and are commercially available. Either piezoresistive or capacitive readout of proof mass displacement can be employed. These devices also use multiple wafer bonding technology to fabricate sandwich structures to provide overrange protection and damping. More recently, microminiature accelerometers fabricated in polysilicon by surface micromachining were reported (Ristic et al. 1992; Payne and Dinsmore 1991). These accelerometers may also be integrated with CMOS electronics. Several commercial products are available.

In order to achieve wider dynamic range and address higher performance applications such as inertial navigation, conventional accelerometers frequently use closed-loop, force-rebalance techniques. Several closed-loop silicon accelerometers have been reported in the United States. One uses a bulk silicon structure (Henrion et al. 1990), while another employs a surface micromachined single-crystal structure (Boxenhorn and Greiff 1990) and consists of a polysilicon accelerometer integrated with CMOS detection circuitry (Yun, Howe, and Gray 1992).

For critical applications such as air bag deployment, efforts are under way to develop self-test capability in accelerometers. In one such device (Allen, Terry, and DeBruin 1990), an input signal heats an actuation beam that applies a known force to the device structure. Another concept uses electrostatic forces to apply the test signal to the accelerometer (Pourahmadi, Christel, and Petersen 1992). If proper response is obtained, the functionality of the accelerometer is confirmed. This rather complex device structure is another example of the added sensor capabilities made possible by MEMS technology.

Several other types of sensors for mechanical variables are being developed. A vibratory silicon gyroscope has been demonstrated (Greiff et al. 1991). This device is a doubly gimbaled structure supported by torsional flexures. The gimbaled mass is driven into torsional vibration. Coriolis forces during rotation transfer energy into vibration in the orthogonal torsional mode. The amplitude of this second vibration is a measure of input rotation rate. A micromachined silicon condenser hydrophone has also been reported (Bernstein 1992). This device uses a surface-micromachined silicon plate that is deflected by the acoustic wave, causing a capacitance change with respect to an overlying micromachined electrode. High acoustic sensitivity is obtained in a device only 1 mm on a side, comparable to ferroelectric hydrophones many times larger.

Complex, micromachined structures can be designed and fabricated to have unique thermal properties that can be useful for sensors. Microminiature versions of thermal mass flowmeters have been demonstrated to be more sensitive, faster responding, and lower in power than macroscopic devices (Ohnstein et al. 1990; Tai, Muller, and Howe 1985). While the basic thermal principles of operation are similar, the miniature devices have significantly better performance due solely to their small size. A fully-integrated, miniature Pirani pressure/vacuum gauge has been reported (Mastrangelo and Muller 1991). This device measures absolute pressure between 10^1 to 10^4 Pa by the pressure dependent change in thermal conductivity. The MEMS device is very low in power, and is fully integrated with NMOS circuitry giving a digital output. Microstructure bolometer devices have useful sensitivity to infrared radiation and can be easily fabricated as arrays of miniature devices. Thermal infrared detectors (Choi and Wise 1986) and very large imaging arrays (Guckel et al. 1993b) are also under development.

MEMS technology may also be advantageously combined with optics for sensing. One example is the fabrication of a miniature Fabry-Perot interferometer for optical measurements in the near infrared spectral region (Jerman, Clift, and Mallinson 1990). Another demonstration is the use of light beams to both excite a microminiature resonant beam strain sensor and to sense the beam's vibrational motion (Guckel et al. 1993b).

In an advanced concept, micromachined structures have been fabricated as extremely sensitive displacement transducers using electron tunneling concepts. The devices employ a microfabricated tunneling tip in close proximity to a surface. Resolution of 10^{-2} Å displacements between tip and surface by variation in the tunnel current have been demonstrated. Applications to Golay cell infrared detectors, accelerometers, and seismometers are being explored. Such extremely high displacement sensitivity raises questions of dynamic range and stability that must be addressed.

As described above, there are many significant developments under way in the United States for sensors for new variables, new structures and operating principles, with improved performance, and reduced cost. However, many issues remain in addressing potential practical applications. The specialized nature of many MEMS fabrication processes makes cost-effective fabrication an issue for low to moderate volume applications. High reliability and stability in real operating environments are critical requirements for many sensors. These requirements are difficult to achieve, and continued development is required for many applications and products.

The important questions of cost, reliability, and performance go beyond the basic sensor element itself. The sensor package can have a dominant effect. New packaging and assembly schemes, including integrated wafer-level packaging, are being developed to address these issues, and are described in another section of this report. Finally, integration of sensors and electronic circuitry into more sophisticated instrumentation subsystems is an increasing trend. These smart sensors can provide compensation, linearization, output ranging, two-way communication, and many other functions.

4. MICROACTUATORS: TECHNOLOGY, DEVICES, AND IDEAS IN THE UNITED STATES (Richard S. Muller)

Historically, bulk micromachining, in which a single-crystal substrate is formed into a micromechanical element, comes before surface micromachining. In surface micromachining, deposited layers over the substrate are machined into mechanical elements. However, the first surface micromachined device (Nathanson et al. 1967) was coincidentally the first actuated micromechanical device. In the early 1980s, when surface micromachining made startling advances as a consequence of utilizing materials and processes that had been well characterized by the integrated-circuits industry, once again the first surface micromachined device was demonstrated as an actuated microdevice (Howe and Muller 1986). Both of these microactuated devices relied on Coulombic forcing functions that could easily be activated by changing voltage levels.

An expanding horizon for actuated micromechanisms has helped to propel research and development on increasingly sophisticated devices and microsystems. Microactuators are becoming recognized as nearly indispensable elements for force-balanced systems, for the control of tiny movements, for self-adjusting systems to accommodate environmental and material-aging variations, and for precise measurement systems such as those employing resonators.

The economical production of microactuated elements integrated into sophisticated systems will open very large areas of opportunity in microsensors, microoptics, microfluidics, and microrobotics. The great potential of microactuated elements has become recognized, and research and development on microactuators in the United States is intense and growing.

Research Locations

In the United States, research at universities has played an important role in developing microactuation. In the mid-eighties, there were identifiable research projects on microactuated devices at the University of California at Berkeley, the University of Utah, Stanford University, and the Massachusetts Institute of Technology. In 1987, an NSF panel identified movable micromechanisms as being a very significant development in a publication called *Small Machines, Large Opportunities.* The NSF publication introduced the word "microdynamics," which was used later as a stand-alone title for a keynote lecture at Transducers '89 in Montreux, Switzerland (Muller 1990).

As the mid-nineties approach, a growing list of campuses, in addition to the universities named above, have targeted research on microactuated devices using diverse technologies and focusing on a variety of applications. These universities include: Case Western Reserve University, Cornell University, Georgia Institute of Technology, the University of California at Los Angeles, the University of Michigan, and the University of Wisconsin.

In industry and at the national laboratories, there has been lesser publication of microactuation ideas -- both because much work is still in progress and also because publication is certainly not an industrial priority. Microactuation does, however, play an important role as a force-balancing means in microaccelerometers as described by Analog Devices, Motorola, IC Sensors, and Lucas NovaSensor. The digital-mirror display device of Texas Instruments qualifies as an important application for microactuation, as does the work of small companies like Redwood

Semiconductors, which is developing microvalves using fluidic phase-change principles (Zdeblick and Angell 1987).

Prime Movers

Actuating forces that are under the most study at this time for applications to microdynamics include: electrostatic, resonant impulse transfer, fluidic phase change, magnetic, pneumatic, piezoelectric, ultrasonic, thermal bimorph, piezoelectric bimorph, and shape memory alloy.

In the United States at present, there is research on devices employing virtually all of these prime movers; however, the focus is not spread uniformly across the list. Electrostatic actuation is naturally in a favorable position if sufficient force can be gained from it for microactuation because electrostatic forcing can be so comfortably integrated with microelectronics. Thus, for example, two major MEMS for industry, the microaccelerometer of Analog Devices (Payne and Dinsmore 1991) and the modulated mirror array of Texas Instruments (Sampsell 1993a), employ electrostatic forcing either to balance accelerative forces (in the first case) or to move tiny mirrors in an array (in the second). Electrostatic drive has also been used to power a very tiny microgripper made from polycrystalline silicon (Kim et al. 1990) with a maximum opening to 20 μm.

To provide a snapshot of the broad activity in microactuation in the United States at present, a bibliography of recent papers describing trends in U.S. research on microactuation is included on pages 285-287. The listing includes papers on comb drive, resonators, rotating micromotors, friction and sticking, magnetic drive, ultrasonic drive, piezoelectric drive, and microactuated electrooptic devices. The first section provides a view of recent research on comb-drive devices, both surface micromachined (Fan and Crawford 1993; Tang, Lim, and Howe 1989) and using monocrystalline silicon (MacDonald 1992). Following the first demonstration of electrostatic comb drives by W.C. Tang and R.T. Howe (Tang, Nguyen, and Howe 1989), these drivers became a prime power source for microresonators. Comb drivers are used for two of the resonators in the next grouping of papers (Lee, Ljung, and Pisano 1990; Nguyen and Howe 1993) while the work of Boustra et al. (1992) at Michigan employs a piezoelectric driver for a resonating cantilever.

Continued research in the United States on rotating micromotors has produced high rpm devices (above 10,000 rpm), and showed ways to reduce frictional effects that have been found to dominate the mechanics for these devices. Activity on rotating micromotors has been strong at Case Western Reserve University. Two papers on microdynamical friction provide some picture of present research on its control. Four papers are cited that show the growing efforts on magnetic actuation, which has been an area of concentration at the University of Wisconsin and at Georgia Institute of Technology. A paper by Busch-Vishniac at the University of Texas contrasts microactuation with other prime movers for microdynamics (1992). The research on ultrasonic Lamb waves at the University of California has shown the possibilities for using this means for moving solid elements and also for pumping and mixing fluids; Moroney, White, and Howe are authors of a paper describing this research (1991). A growing focus on piezoelectricity derived from thin films is highlighted in three papers that are complemented by the Boustra paper (1992) cited in the group of papers on resonators. The last section of the bibliography contains two papers from Carnegie Mellon University and from Stanford University that highlight an emerging concentration of research on microelectrooptical devices.

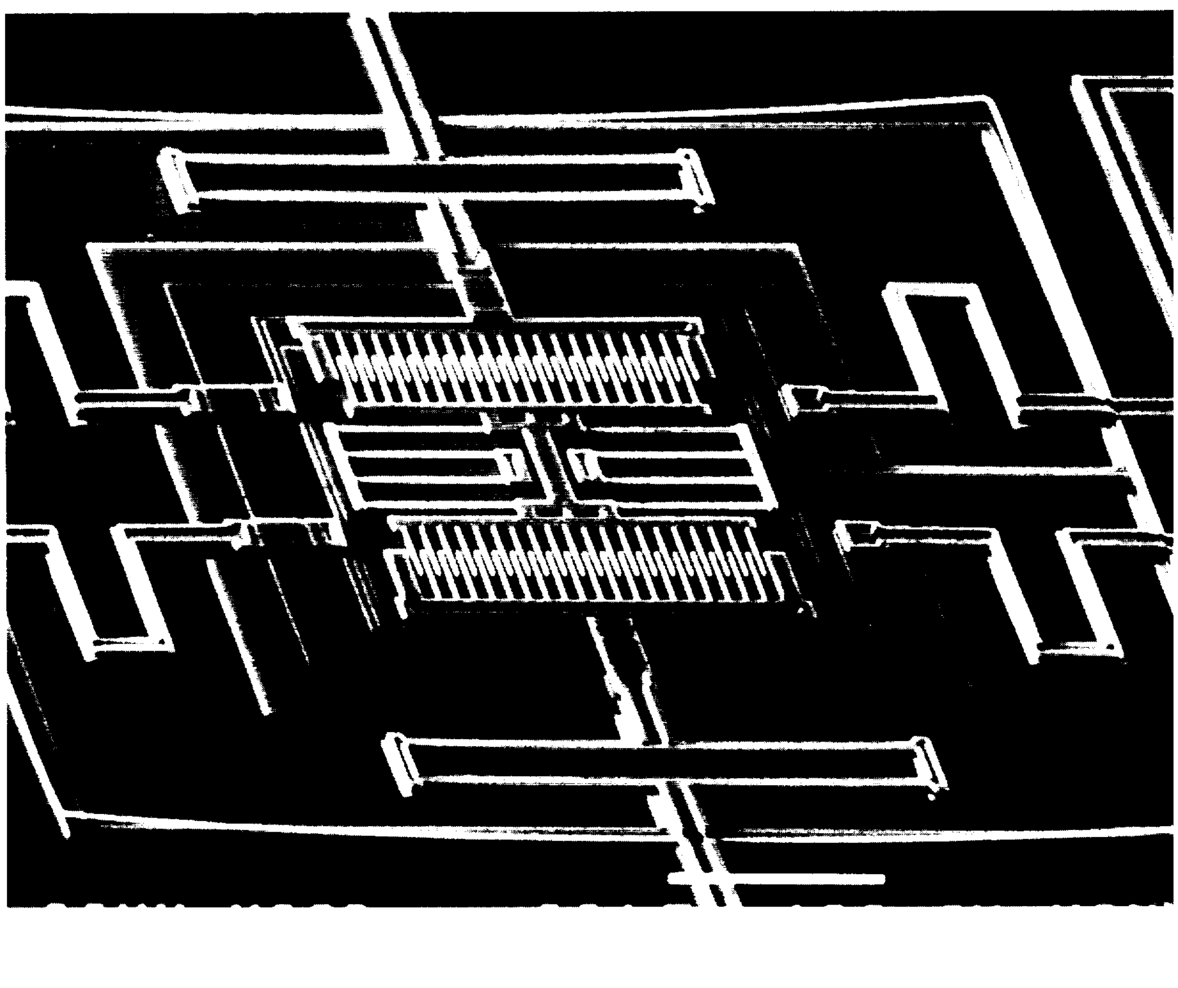

Figure D.5. SEM view of a four-port electrostatically-driven lateral micromechanical resonator developed at the University of California at Berkeley (Nguyen and Howe 1992).

6. SENSOR-CIRCUIT INTEGRATION AND SYSTEM PARTITIONING (Kensall D. Wise)

Throughout their history, sensors have traditionally been viewed as components to be purchased as needed and added to existing systems to complete their interface with the nonelectronic world. This view persists in many areas of industry, especially in the United States, and yet there is a growing recognition that these devices should in fact be viewed as system elements and be developed as an integral part of the overall system design. As components, sensors are rather limited in function by the fixed systems that represent their market, and there is limited ability to do more than replace earlier components. Thus, the interfaces remain 5 V analog signal lines connected by point-to-point wiring, and auxiliary functions are difficult to introduce. Such arrangements do not take full advantage of the capabilities of silicon as a transducer substrate, and do little to spark the progress that the sensor/actuator field should represent. On the other hand, the ability to build additional functions into the transducer module, such as self-testing, autocalibration, digital compensation, and digital bus compatibility, would both improve system reliability and decrease system cost.

Many major companies in the United States are today in the process of developing mixed sensor/actuator systems (MEMS) that merge electronics with transducers to produce microinstrumentation systems in a single module and, in some cases, on a single chip (Wise and Najafi 1991). This includes major efforts at most of the automotive companies, in the environmental controls industry (HVAC), and in the design of industrial process controls. SEMATECH, for example, is working to define a sensor bus for intratool use in semiconductor process equipment. Such buses will replace point-to-point wiring between dozens of sensors and actuators, and the host controller, with bus communication. It would appear that in applications where distributed sensing and actuation are required and where hierarchical control is used, such microinstruments will become commonplace within a decade, at least in simple forms. Figure D.6 shows a diagram of such a system (Najafi and Wise 1990). Because of their suitability for miniaturization, these devices will likely concentrate initially on sensing, with actuation used at first as a means for providing functions like self-testing. Exceptions are likely to be the use of microvalves for the implementation of flow control or in instruments such as sampling systems for use in medical diagnostics or in miniature gas chromatography systems. Inertial guidance systems will make extensive use of microactuators to provide drive to the sensors, as will other forms of resonant sensors.

From a system point of view, the level of integration used in these microsystems will be decided primarily by cost and reliability issues. It is interesting that in industries where volumes are high and reliability is paramount, monolithic implementations are being pursued. In situations where expected volumes are lower, hybrid approaches

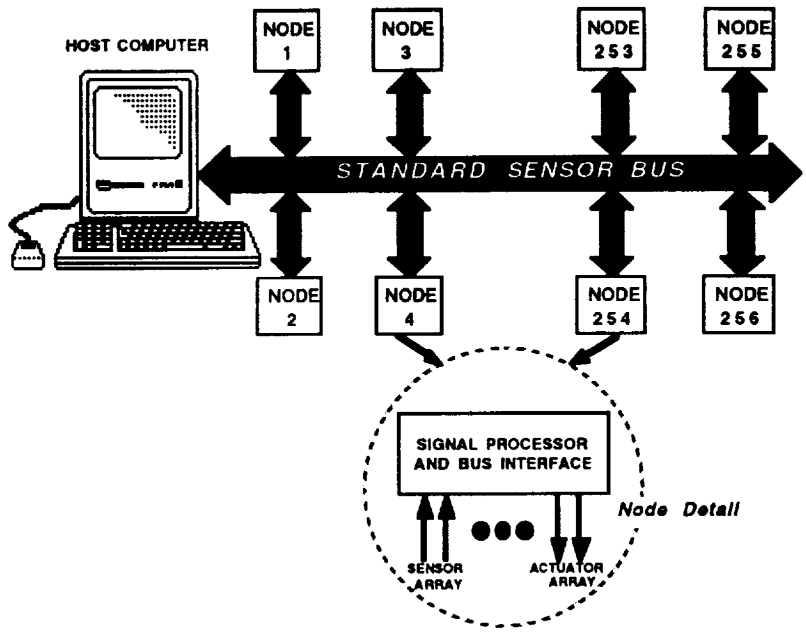

Figure D.6. General organization of a distributed sensing system. Each node here is a monolithic or hybrid module comprising a microelectromechanical system of sensors, actuators, interface circuitry, and a microcontroller/microprocessor chip.

are being explored, as might be expected. Processes for merging transducers and circuits are being pursued based on bulk micromachining (Wise and Najafi 1991b; Ji and Wise 1992), surface micromachining (Mastrangelo and Muller 1991; Yun, Howe, and Gray 1992; Nguyen and Howe 1992), and combinations of the two (Kong, Orr, and Wise 1993). Figure D.7 shows typical process flows. In either case, the goal is to modify the circuit portion of the process as little as possible in order to make the overall process as directly compatible as possible with those in commercial foundries. This is important to allow adoption of the technologies by small to medium size companies that may not have their own fabrication facilities, and is also important for lower-volume applications in which the development costs for a full-custom process might be more difficult to recover. For bulk micromachined processes, some diffusions must typically be performed at the front-end of the process flow to embed appropriate etch-stops in the material. The circuit process then continues without interruption until final metal. This must either be a material that will not be attacked in the silicon etchant used or it must be protected using dielectric overlays. In the latter case, special inlays at the bonding pads are still required. The micromachining etch must be performed as the last step in the process, where it can also serve for die separation if desired. For surface micromachined structures, the transducers are formed using post-processing steps, after circuit formation. Here, special metal may still be required to permit high-temperature annealing of polysilicon microstructures (Yun, Howe, and Gray 1992).

In this case, a high-quality dielectric overcoat (e.g., with silicon nitride) of the entire chip is required to shield it from the final sacrificial etch. This release should be performed before die separation, but in this case the delicate microstructures must be protected during the die separation procedure used. This is not a simple challenge, but has been successfully implemented commercially (Payne and Dinsmore 1991).

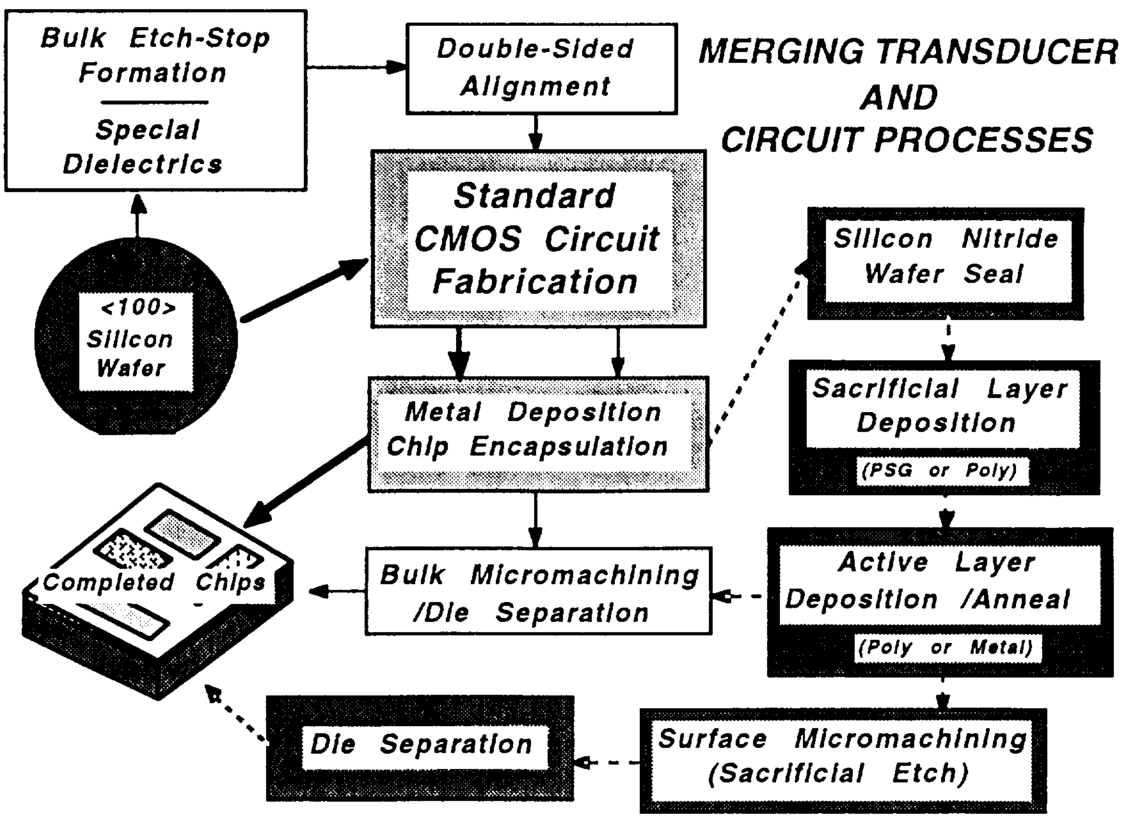

Figure D.7. Process flows for merging bulk- and surface-micromachined transducers with on-chip circuitry.

Figure D.8 shows an uncooled monolithic thermal line imager implemented recently using on-chip CMOS circuitry and bulk-micromachining. Each of the thirty-two stress-relieved dielectric windows supports forty polysilicon-metal thermocouples that convert the temperature rise on the window induced by incident radiation into an electrical output signal (Baer et al. 1991). The windows measure 400 μm x 800 μm with a responsivity of 60 to 80 V/W, a time constant of about 5 msec, and a remote temperature resolution of about 0.2 °C. On-chip circuitry multiplexes the output signals, measures the ambient temperature, and can provide self-testing. An alternative to such back-etched structures are devices that are based on front-side undercut devices (Baltes and Moser 1993). These are being pursued in both the United States and Europe because of their compatibility with standard foundry processing up to the final front-side etch, but have been used more for thermal devices than for mechanical structures. Figure D.9 shows a thermally-based absolute pressure sensor complete with MOS detection circuitry recently developed at the University of California at Berkeley (Mastrangelo and Muller 1991). This device uses a heated micromachined polysilicon beam to measure the thermal conductivity of the surrounding gas and hence its pressure. Another example of this technology is found in a microelectromechanical filter chip, also developed at Berkeley, which contains a variety of electrostatically-driven mechanical elements together with integrated electronics (Nguyen and Howe 1992).

One of the higher levels of circuit integration on a micromachined structure is shown in Figure D.10. Multichannel silicon probes are under development for the stimulation of biological neural networks with high precision, both spatially and in terms of charge delivery to the tissue (Tanghe and Wise 1992). The probe structure is defined using a deep boron diffusion in a single-sided bulk process and incorporates CMOS circuitry to provide per-channel 8-bit current control over sixteen electrode sites using only five external leads. The circuitry accepts serial input data at 4 MHz to select the site and current level desired and dissipates only 80 μW from ± 5 V supplies when idle. The currents generated cover a biphasic range of ± 254 μA with a resolution of 2 μA. The circuitry permits the IrO sites to be activated by voltametry from off-chip, provides per-channel pulse timeout to prevent accidental overstimulation, signals the external world in the event of certain trouble conditions, and is implemented using about 7,000 transistors in a circuit area of 11 mm^2 in 3 μm features.

Solid-state sensors have evolved over the past two decades from devices having one-way analog outputs through digitally-addressed analog-output modules to fully integrated sensor/actuator systems with onboard microcomputers or microcontrollers. Although relatively high levels of monolithic integration are being pursued in connection with the last devices, it seems likely that the levels of integration on monolithic MEMS chips will remain relatively low prior to 1995, reaching levels above 10,000 transistors only after that date. The integration of full microcontrollers on such chips seems likely for some applications by the year 2000, but even at that time, most MEMS applications will likely remain hybrid, employing standard commercial processors together with front-end MEMS chips containing the transducers along with a modest amount of electronics. Figure D.11 shows such a configuration. The identification of appropriate high-volume targets for commercialization remains a challenge and a concern in pacing industrial developments.

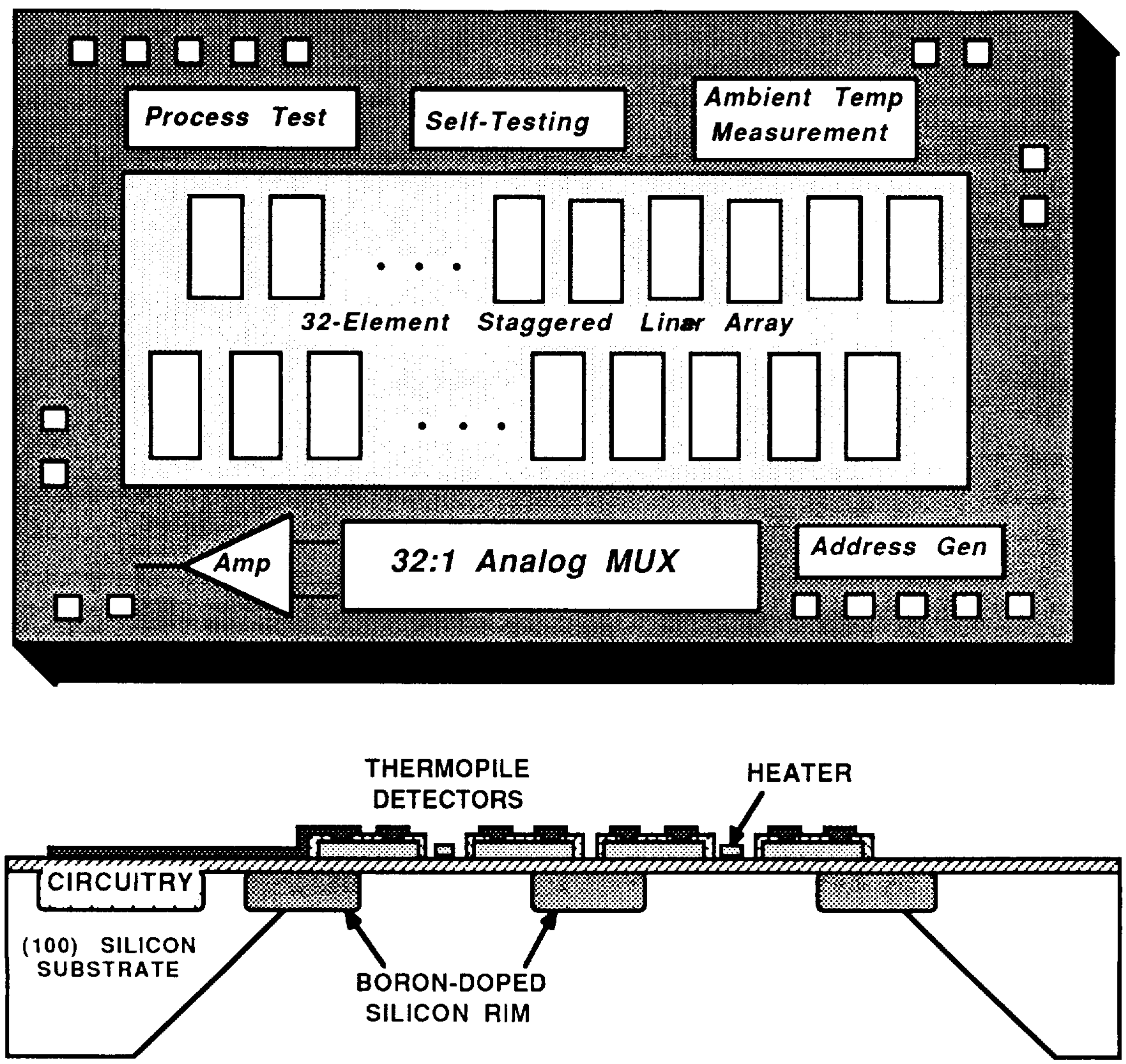

Figure D.8. Top view and cross-section of a 32-element thermal line imager formed by series-connected thermocouple arrays supported on micromachined dielectric windows. A top view of a portion of the imager is shown below with the windows back-lighted. The windows measure 400 μm x 800 μm in size.

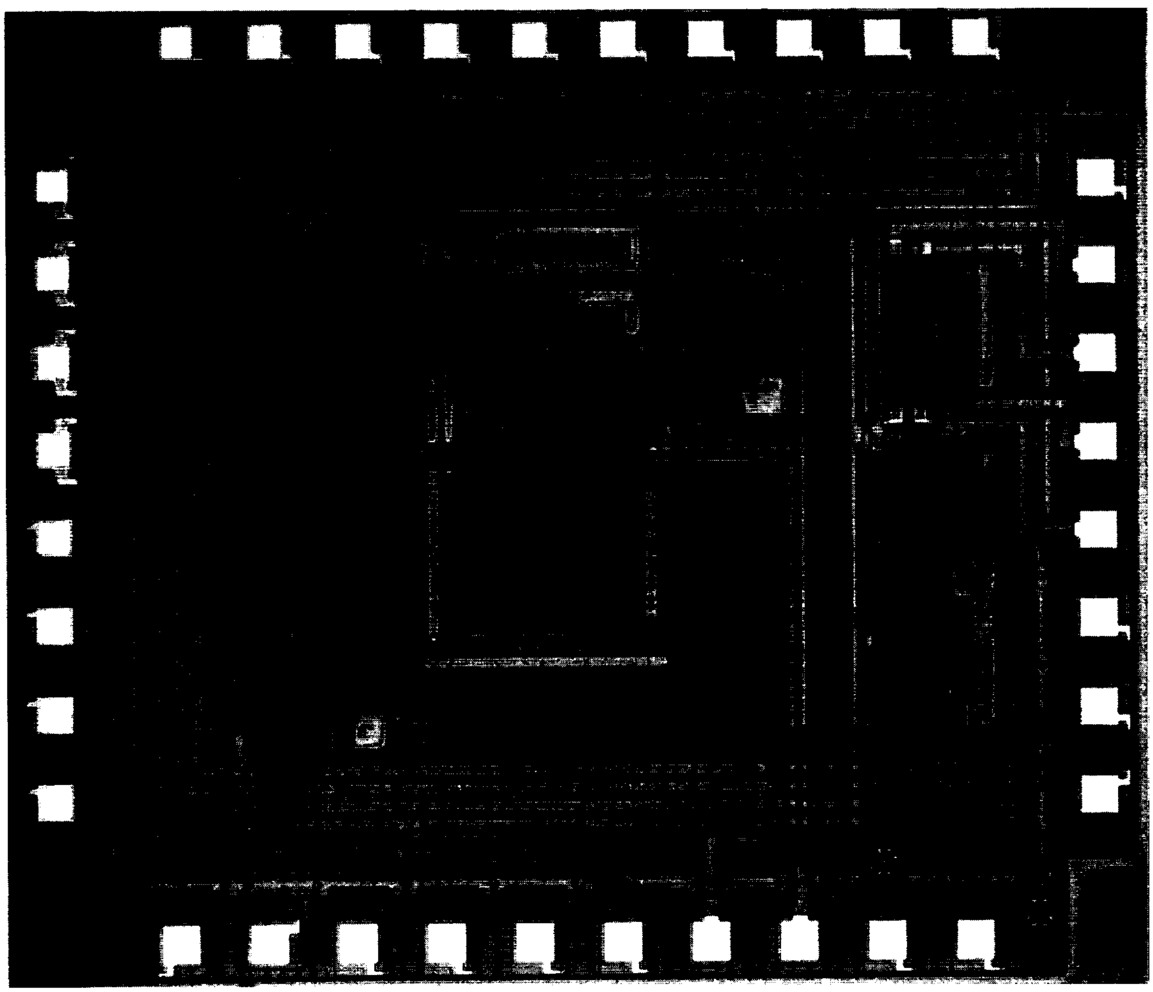

Figure D.9. Top view of an integrated thermally-based absolute pressure sensor with MOS readout electronics (Mastrangelo and Wise 1992).

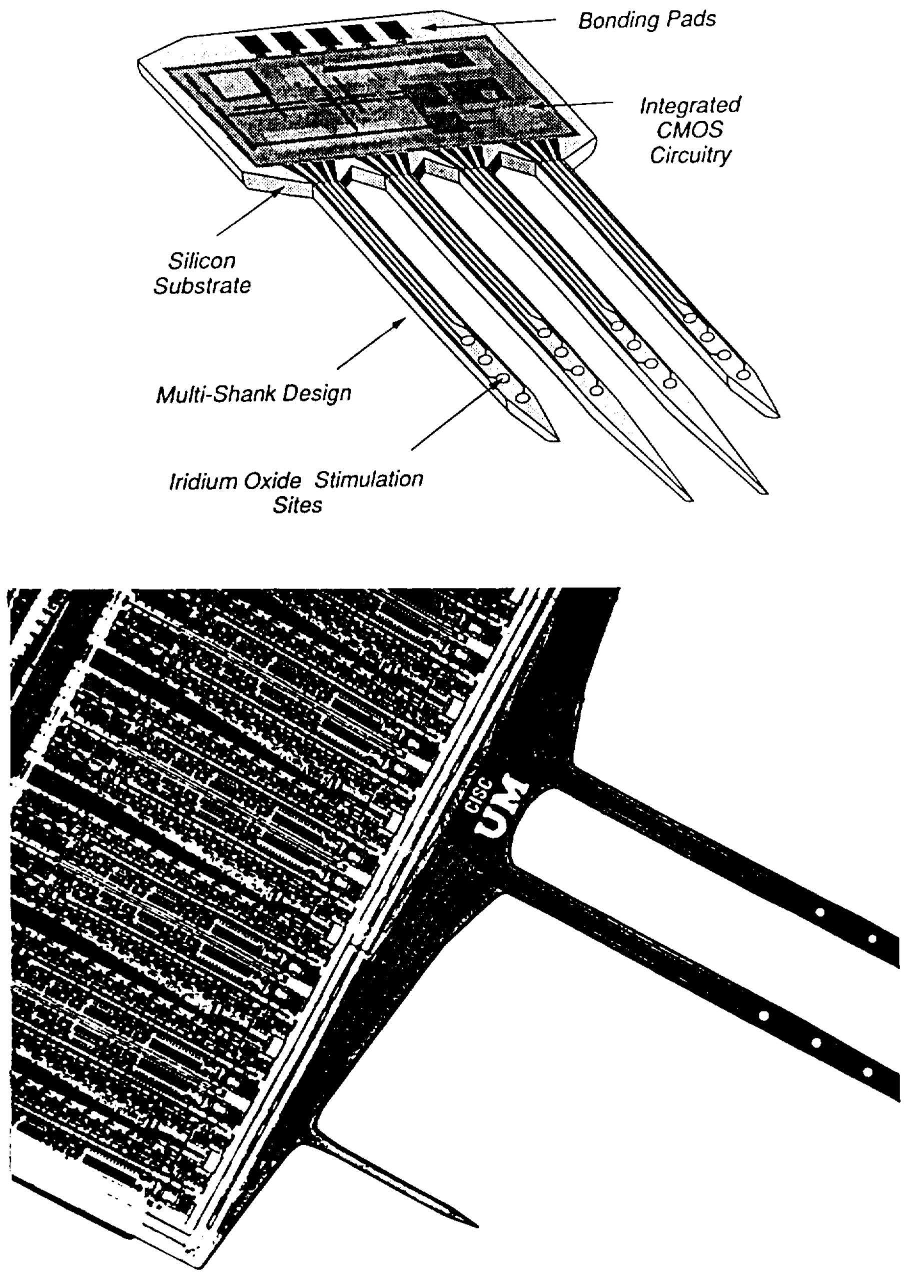

Figure D.10. Drawing and top view of a micromachined neural stimulating probe containing 16 8-bit CMOS digital-to-analog converters and associated control circuitry.

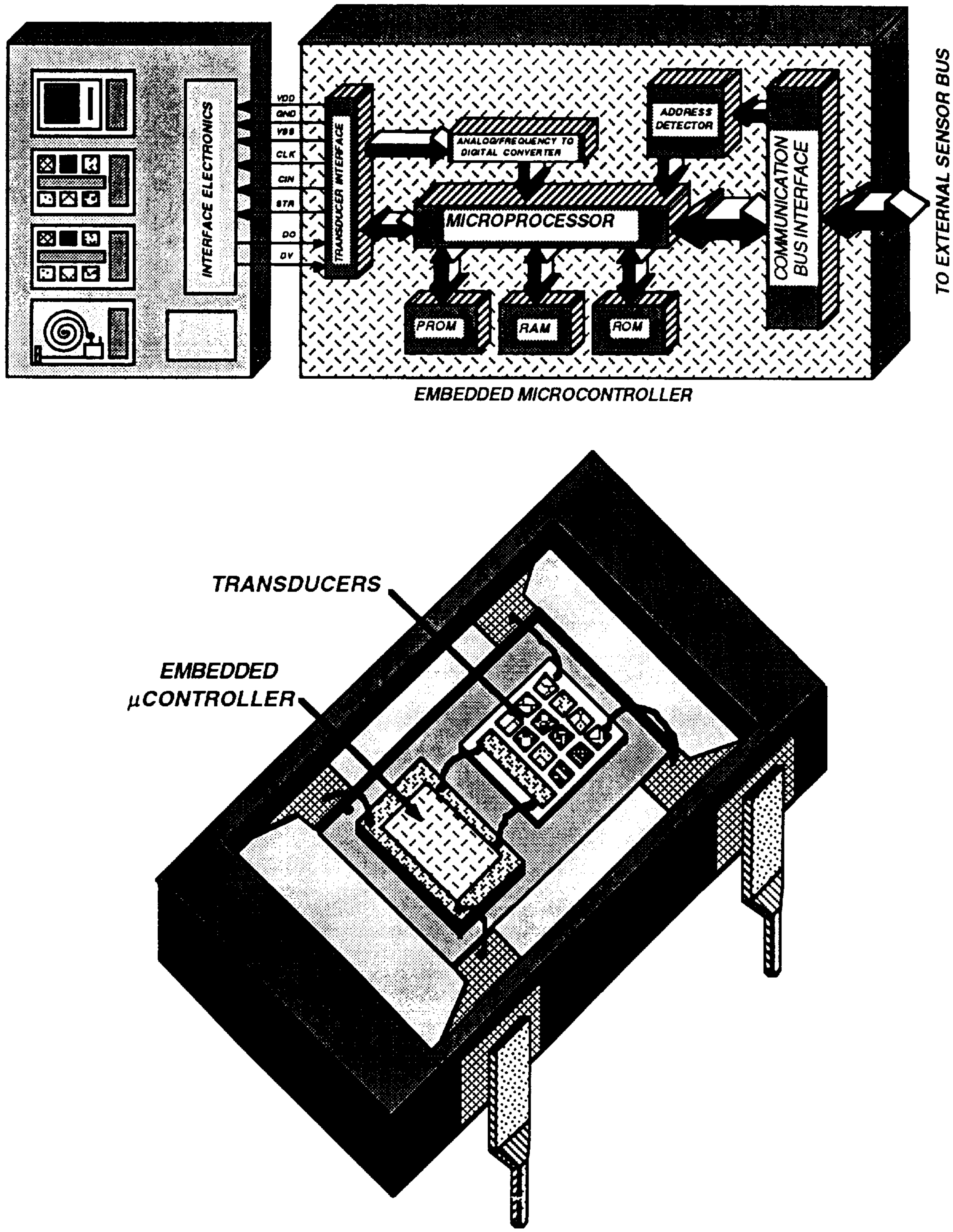

Figure D.11. Structure for emerging high-end microsystems, employing a front-end chip containing transducers and interface electronics along with a microcontroller chip to give the module flexibility and stored-program intelligence.

Bus standards will certainly be adopted before the end of this decade. These will probably be specific to particular industries. Coordinated efforts such as the one at SEMATECH could unify standards within a particular industry, but commonality among different industries appears unlikely. Even in the automotive industry, several different bus standards are still being promoted, and the requirements there are viewed as different from those in the industrial process control area. In automotive, each node must be able to communicate with any other node, whereas in industrial controls it is probably sufficient if each can communicate only with the host controller, and then primarily in response to commands received from it. Greater interface commonality is likely to be achieved through the use of programmable interfaces, and perhaps through overdesign for some applications.

One of the primary reasons for embedding a microcontroller in the sensing node is to improve the accuracy of sensor/actuator calibration procedures. Historically, all sensors have needed compensation for offset, slope errors, and output temperature sensitivity. These trims have normally been implemented using laser trimmed resistor networks. Such compensation is typically adequate only if the required compensation is linear and hence is viable only over a restricted dynamic range. The use of digital compensation using lookup tables or polynomial coefficients stored in EPROM can follow very nonlinear sensor outputs. The first digitally-compensated devices are now beginning to appear, and have produced roughly order-of-magnitude improvements in accuracy (Wise and Najafi 1991a). In theory, such an approach should allow the system to utilize the full performance available from the transducer, limited only by the device stability over time. As in other areas of microelectronics, sophisticated procedures once reserved only for high-end devices are likely to pervade even low-end devices within the next decade. The area of testing and compensation has received very little attention in the literature in the United States and probably globally. But it is of great importance to coming systems, and needs to be addressed more vigorously.

During the past year, several efforts to make MEMS available through foundry services have been undertaken. The most notable efforts are at MOSIS and at MCNC. The goal of these efforts is to make MEMS much more widely available, both to university researchers and to industrial organizations seeking a rapid prototyping service. As part of these efforts, it is likely that a few standard processes will be employed. As in the microelectronics industry, larger companies will optimize their internal processes to meet their own particular needs. Even in such companies, however, only a few different processes will be supported, and they are likely to differ from company to company.

Thus, in the United States there appears to be a pronounced trend toward merging transducers and circuits monolithically, and toward merging these chips, employing modest levels of integration, with commercial microcontrollers to form microinstruments (Wise 1993). Most of these efforts are still in the research stage, with commercial products expected during the latter half of the decade. After that time, a continuous series of enhancements are expected.

6. ADVANCED PACKAGING, MICROASSEMBLY, AND TESTING TECHNIQUES (Stephen C. Jacobsen)

International Priorities – the Role of MEMS Technology

Together with other business and governmental activities, technology can contribute significantly to the solution of international problems. The means by which technology contributes is through the application of products and processes such as those listed for MEMS in Figure D.12. Such new products typically evolve by including emerging component-level subsystems developed by projects that utilize the new technology. The new subsystems are typically aimed at providing discriminating product features that improve performance, reliability and/or cost, and enhance other factors such as recyclability, safety, and use of strategic materials.

New Products

Increasing Complexity with Better Performance and Economy. Modern machines are evolving toward increasing complexity levels. The trend, which is unavoidable, is driven by populations seeking new products and services, and a simultaneous imperative to address environmental and safety objectives. The architecture of the new machines is evolving away from collections of barely-compatible, unrelated components toward systems planned from the outset as integrated machines destined for a complete life cycle compatible with the goals mentioned above. The machines are information intensive and involve different computational and moving parts as outlined in Figure D.13a (upper left). The machines, which will be called here Information-Driven Machines that Move (IDMTMs), serve five basic functions: as models, sensors, controllers, effectors, and interfaces. The design and manufacture of IDMTMs require development of subcomponents of many types and from different disciplines, as depicted in Figure D.13b (upper right).

Product complexity is increasing across-the-board in many areas, ranging from consumer products to manufacturing machinery, as shown in Figure D.12. Figure D.13c (lower left) shows a progression in complexity in robotic systems, with sensors and actuators increasing from just a few to hundreds in only a decade. Figure D.13d shows that even in a subarea of the robot, the effectors (muscles), complexity has progressed substantially from just an actuator and sensor and some wire. Sensors, actuators, controllers, and structures must now be considered as not just randomly installed elements but as integral machine subsystems connected to computers and other peripherals over digital multiplexed buses.

MEMS APPLICATIONS
LARGE MARKETS

COMPUTER SUBSYSTEMS
Disk Drives, Printers, Plotters, Mouses, Joy Sticks

HUMAN INTERFACES WITH COMPUTERS
Human/Computer Interfaces for Virtual Worlds
Goniometers, Mouses, Joy Sticks,Displays

AUTOMOBILES
Transmissions, Suspension , Braking, Controls

CONSUMER PRODUCTS
VCR, CD, Cameras, Toys, Games, Home Equip.

AIRCRAFT
Flaps, Gear, Engine, Life Support, Weapons

MATERIALS HANDLING
Inventory systems, vehicles, transfer machines

INDUSTRIAL EQUIPMENT
Testing, agriculture, construction , forestry, lifts

MANUFACTURING MACHINERY
Molding, Forming, Machining, Soldering, Placing

ROBOTICS & TELEOPERATION
Entertainment, Manufacturing, Utilities, Nuclear
Undersea, Clean Rooms, Laboratory, Security

MEDICAL SYSTEMS
Minimally-Invasive Surgical Systems
Drug Delivery Systems, Medical Imaging Systems

Figure D.12. Application areas for microelectromechanical systems.

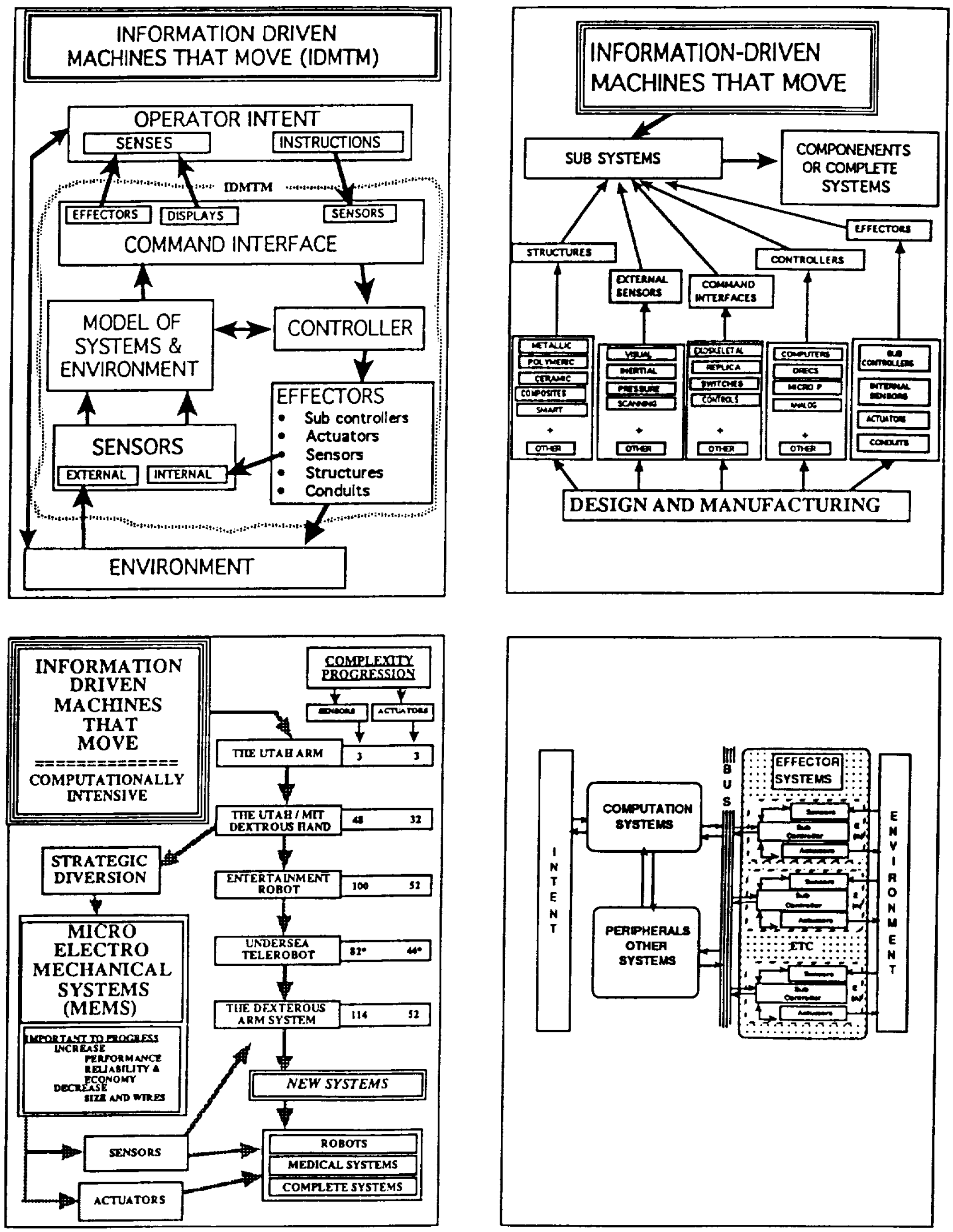

Figure D.13a-d. Information-driven machines that move. Parts a, b, c, and d, are located in the upper left, upper right, lower left, and lower right, respectively.

As noted in the previous section, the architecture that defines the arrangement of the subsystems is also changing. Larger numbers of sensors and actuators are being interconnected to control higher modes of machine operation. Complex control requires a model-based approach, which necessitates an expansion of local chip-based control circuits. New methods for the arrangement and interpretation of sensor information are being developed, as shown in Figure D.14b. Sensor and actuator design must now address economic constraints and target additional properties, as reviewed in Figures D.14c and D.14d.

Very Small Machines

The new technology area of MEMS is focused on developing the design and fabrication resources necessary to produce small electromechanical structures that can be combined to manufacture Very Small Machines (VSM). The VSMs will function in a variety of physical regimes, including: mechanical, electrical, optical, thermal, chemical and others. In fact, VSMs have been designed and manufactured for years. The goal of VSMs has been to use size advantages (scaling laws) to achieve enhanced performance in areas such as speed, complex function, low weight, and packaging advantages. In most cases, however, small size has produced desired performance levels but has not achieved the cost and reliability levels necessary for widespread use in lower-level products.

Over the last few years, MEMS technology has been brewing in various laboratories. This approach should allow the economic manufacture of microsystems with the simultaneous achievement of reliability and performance goals.

MEMS (Microelectromechanical Systems)

MEMS can contribute significantly to the economic production of VSMs and other components for conventional products. As described in the earlier sections of this report, MEMS are very small systems fabricated using primarily silicon micromachining and VLSI processes. Such machines consist of mechanically and electrically active subelements that range in size from 0.5 to 500 μm. MEMS represents a new field that will revolutionize many products for military and commercial applications and should permit the development of better subsystems based on mechanical, electrical, fluid, thermal, chemical, optical, and other phenomena.

The generation of concepts, design tools, and fabrication approaches is already moving ahead. It should be noted here that MEMS and VSMs are not specific devices or processes, but approaches that include new design tools, fabrication processes, control approaches, and integration strategies. The appeal of the approach is soundly based in potential near-term economic advantages and associated competitive advantages.

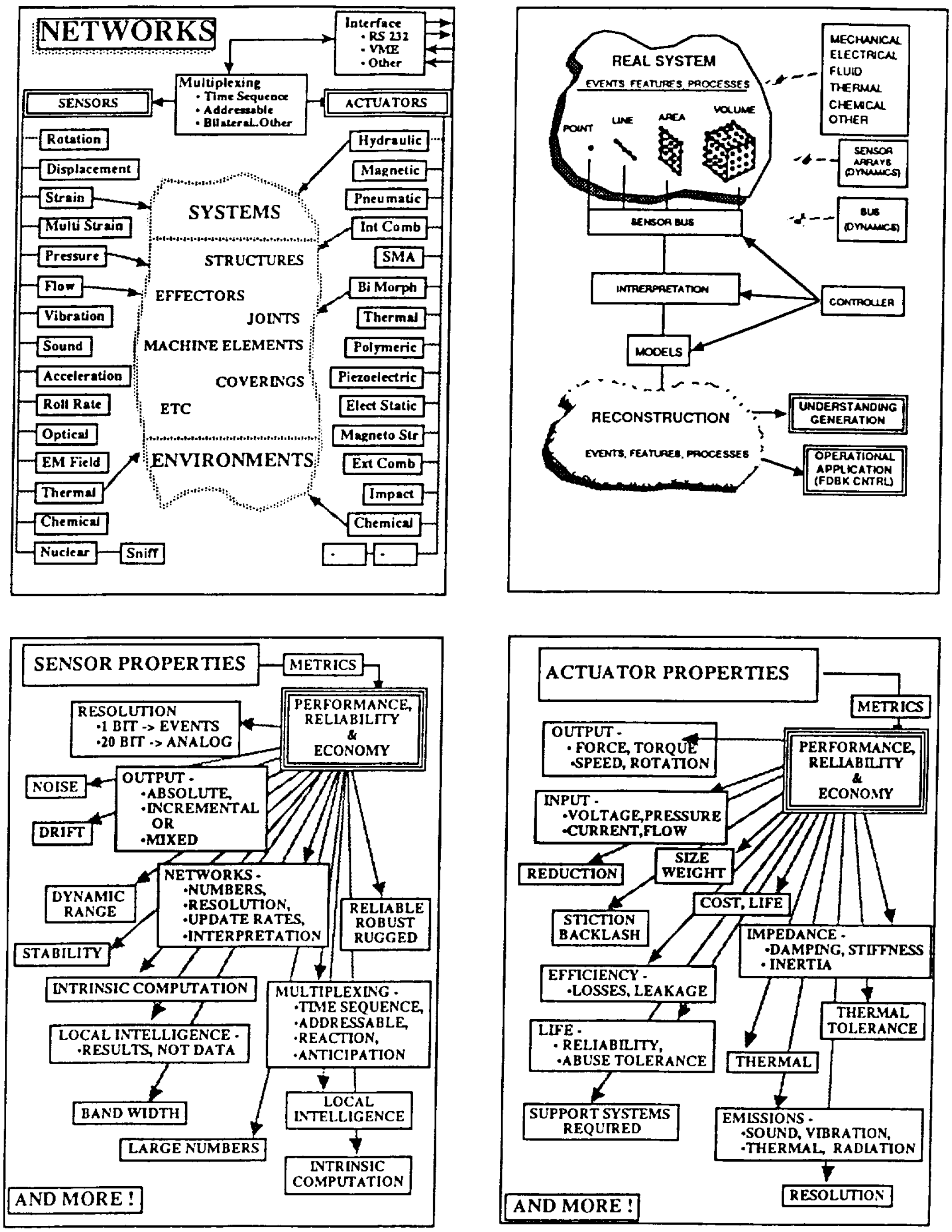

Figure D.14. Issues in the development of sensors, actuators, and MEMS.

The basic advantages of MEMS are briefly listed in Figure D.15 along with its status and barriers. Advantages include not only cost and performance but also the prospect of practical networked systems. As discussed above in section 5 of this appendix, nets allow distributed computation for local interpretation and multiplexing, which reduces wiring and permits substantial improvements in design flexibility (i.e., components can be placed where convenient, do what is required, be commanded strategically, and be easier to maintain).

MEMS: Targets, Status, Barriers, and Approach

Development targets in laboratories around the world include: sensors, actuators, systems, design tools, packaging approaches, and integration strategies.

Sensor development projects under way include:

- Mechanical (position, load, vibration, impact)
- Fluid (pressure, flow, sound)
- Inertial (acceleration, roll, velocity, location)
- Optical (incident radiation, imaging)
- Thermal (temperature, radiation, distortion)
- Chemical (industrial chemicals, medical processes)
- Others (nuclear, EM fields)

Actuator developments are focused on almost any material that will alter size or shape in response to an energetic input. For local self-management, many actuation schemes also include the placement of sensors for local actuator control. Approaches include:

- magnetic field
- magnetostrictive
- shape memory alloys
- chemical
- electrostatic field
- piezoelectric bimorph
- phase transition
- polymeric
- electrostrictive
- thermal expansion
- impact
- and others

Systems are being developed that include all elements of Figure D.13. These include sensors, actuators, structures, controllers, buses, and computers. Examples include:

- inertial platforms
- virtual reality systems
- optical arrays for light control
- vibration compensated machine tools
- chemical analytic instruments
- embedded sensor-actuator structures
- networked sensor arrays
- smart materials - deformable
- chemical processors
- robots
- fluid control systems
- color displays
- printing systems
- deformable RF antennas
- medical devices
- and others

C-4.

ADVANTAGES OF MEMS

HIGHER PERFORMANCE

VIA SCALING - SMALL PHYSICS & ELEMENTS
- LOW WEIGHT & SIZE
- FAST, PRECISE &RUGGED
- CAN USE RARE SUBSTANCES
- HIGH AREA TO VOLUME RATIOS
- BETTER ISOLATION AND SHIELDING

REDUCED COST

ADVANCED FABRICATION
- AUTOMATED - BATCH
- OPTICAL, E-BEAM, CHEMICAL, ETC

LESS MATERIAL
- THIN COMPLEX-GEOMETRY LAYERS

ALSO

ON-SYSTEM CIRCUITRY
- LOCAL INTELLIGENCE
- NETWORK MULTIPLEXING VIA BUS
- BETTER PROPERTIESINTRINSIC AND COMPUTED
- INTEGRATED ELECTRONICS & MECHANICS

SYSTEM DESIGN FLEXIBILITY
- ECONOMIC SENSORS & ACTUATORS (S & A)
- S & A CAN BE USED IN LARGE NUMBERS
- DISTRIBUTED ARCHITECTURES

MEMS - STATUS & BARRIERS

CURRENT STATUS

DEMONSTRATIONS COMPLETE
- Certain Developments are now Products
- Silicon Micro Machining Procedures Proven
- Feasibility of more Complex Systems Demonstrated

FIELD CAN NOW FOCUS ON REAL DEVELOPMENTS
- Real Products Should be Targeted
- Barriers Below Should be Addressed
- Educational Programs Should be Intensified

BARRIERS TO PROGRESS

DESIGN TOOLS For Sensors, Actuators, Systems
- Geometry, Finite Element, Electronics
- Processes, ElectroMechanical Dynamics

FABRICATION RESOURCES
- VLSI, Si Micromachining, LIGA
- Surfacing, Coating, Shaping, etc

PACKAGING & INTEGRATION
- Explore Concepts for new Challanges
- Develop Real Systems Practical for Commercialization

SYSTEMS ARCHITECTURE
- Explore Systems with Large numbers of Subcomponents
- Systems with Multiplexing and Local Intelligence
- System Integration Issues Must be Addressed

BUSINESS
- Investment, Business Formation, Licensing
- R & D Support, Education, International Issues

Figure D.15. The advantages of MEMS along with its current status and remaining barriers.

Design tools and fabrication systems are also in development. Design tools that already exist are being modified for use in MEMS. New systems are being developed at MIT, the University of Michigan, MCNC, and other locations, to permit integrated design of systems with simultaneous consideration of mechanical, EM field, fluid, and other physical effects.

Developments in MEMS have taken the first steps. Products are on the market and many more commercial successes await only additional effort. Figure D.15b indicates the present status as well as barriers to future progress, which are in five development categories: design tools, fabrication resources, packaging and integration, systems architecture, and business.

The approach for future work must include a balanced view of the following:

- o technology
- o components
- o markets
- o projects
- o products
- o businesses

Manufacturing and Packaging

Manufacturing and packaging issues now loom as substantial barriers to the real development of a large body of the concepts generated by the interested R&D and business communities. It is now being recognized that the approach must become broad-based with fabrication processes (forming, machining, coating, etc.) developed in anticipation of broader issues such as assembly procedures, packaging, and other product-related factors. Many processes (in addition to the classical VLSI-related ones) such as those listed in Figure D.16 are becoming available as they are in larger systems, and nontraditional job-shop resources, such as the effort at MCNC, are emerging.

Packaging of MEMS devices is more complicated than for their electronic or mechanical ancestors. New sensors and actuators must physically interact with the environment and thus require passthroughs for the transmission of fields, photons, fluids, moving shafts, chemicals, and so forth. In fact, packaging and assembly processes will dominate the economics of the final product as well as substantially determine factors related to ruggedness, reliability, and maintenance. For applications and devices requiring direct contact with the environment, recent developments in chip-level encapsulation appear promising in terms of collapsing the package to the chip itself and allowing access to specific transducers via photolithographically-formed openings in the passivating films. Future systems will also require systems with substantially greater levels of three dimensionality. Assembly and packaging methods for generating such systems are in development.

MEMS FABRICATION PROCESSES

Etching	Isotropic	Anisotropic	Dopant Stop
Lithography	Photo	E-beam	
Thin Film Deposit	Sputtering	CVDP	Vapor Dep
Electro Surfacing	Anodizing	Plating	Polishing
Characterization	Profilometer		Interference
Micro Cutting	Laser	E-beam	EDM
Wire Bonding	Ultrasonic	Compression	
Bonding	Adhesives	Thermal	Friction
Surface Processing	Ion Milling	Diffusion	
Welding	Laser	E-beam	Spot
Coating	Resist	Dipping	Powder
Extrusion	Mono	Co	
Forming	Hydro	Stamping	Drawing
Joining	Riveting Soldering	Screwing Brazing	Contact Self Alloy
Lapping	Planar	Spherical	
Machining	Turning EDM	Milling Sawing	Drilling
Molding	Injection Casting	Vacuum Compression	Dipping
Removal	Grinding	Polishing	
Lithography	Planar	Nonplanar	Stereo
Welding	Gas	TIG	Arc

PACKAGING
LEVELS OF ENCLOSURE

Configuration	Sensor Type	Actuator Type
CLOSED - FLOW BY		
	accel, temp	no
CLOSED - FLOW THRU		
	em flow	E-M pump Cent Pump
CLOSED WITH LIGHT PASSAGE		
	sensing array colorimitry	display laser
CLOSED WITH FLEXURE		
	pressure strain	phase based act
OPEN WITH SEALS		
	encoder	motors actuators
OPEN		
	ugh	motors

Figure D.16. Processes used in MEMS fabrication along with the various levels of environmental access required by different types of devices.

7. MEMS DESIGN TECHNIQUES, APPLICATIONS, AND INFRASTRUCTURE (Joseph M. Giachino)

MEMS have been used to describe microminiature systems that are constructed with both IC-based fabrication techniques and other mechanical fabrication techniques. In most cases, an emphasis has been placed on having the techniques compatible with IC techniques to ensure the availability of related electronics close by. Most researchers require that the MEMS be contained within the same package, while some require that a MEMS be contained on a single chip.

To date, the integrated circuit industry has been the technology base that has driven MEMS. This is shown in both the bulk silicon and polysilicon efforts that have been the mainstay of MEMS devices. The MEMS community has made significant advances in the area of deep etching bulk silicon and in surface (sacrificial etching) micromachining with polysilicon. MEMS have driven the silicon community into understanding the mechanical and electrical properties of silicon structures. MEMS have driven researchers to investigate fabrication methods other than IC-based techniques to obtain microdevices. These techniques include LIGA, laser-assisted CVD, electroplating, and electroless plating.

The advantages of the MEMS technology include small size, low power, very high precision in manufacture, and the potential for low cost through batch fabrication. MEMS does offer a challenge in the area of how to effectively package devices that require more than an electrical contact to the outside. Pressure sensors are the most commercially successful MEMS-type sensors to use nonintegrated circuit-type packaging. Hall sensors, magnetoresistive sensors, and silicon accelerometers have all used IC-based packaging. The IC packaging is viable with these devices since the measurand can be introduced without violating the package integrity. Some optical systems use IC-type packages with windows. MEMS will require the development of an extensive capability in packaging to allow the interfacing of sensors to the environment. The very advantage of small size becomes a liability when a device is open to the environment. The general area of MEMS durability is also one that has to be improved. There is not a good understanding of all the mechanisms that lead to wear in moving devices on this scale; however, work to understand these mechanisms is being done by various groups. Proven durability is a major need before MEMS technology can be extended to high reliability, long-term (greater than five years) applications. Proven durability has been shown in pressure sensors and accelerometers. For rotating devices (micromotors), there is still a concern.

The greatest impact of MEMS is likely to be in the medical field. A true MEMS (sensor, actuator, and control) should allow the treatment of patients to improve substantially. The ability to monitor and dispense medicine as required by the patient will improve the treatment of both chronic (i.e., diabetes) and acute (i.e., infectious) conditions.

The key advantages of medical MEMS devices are small size, low power demand, and low cost per function. Small size allows in vivo implants and surgical procedures to be performed in confined spaces. There is extensive work now being done in dispensing systems for drugs that can be delivered as required by the patient. Experimental work has also been done using silicon scissors for surgery and silicon neural probes to study neuron activity. The small size of MEMS structures also makes them ideal for manipulating biological samples at the microscopic level. With scanning probe microscopes, it is possible to watch living cells at the molecular level. In the future, MEMS systems that manipulate genes routinely could be built. MEMS can be fabricated to create a complete sampling system, including sensors to determine what the item is, actuators to move the items about, and electronics to analyze and transmit information and, where appropriate, to do control functions.

MEMS applications to automotive, robotics, and consumer products will also have an impact in the next decade. MEMS systems will allow improved analytical capabilities on the molecular and atomic levels. This means a better understanding of such phenomena as wear. The capability of analyzing, combined with that of manipulating on the atomic level, means that very unique and specialized devices could be fabricated. Vision systems that emulate the human eye are not unreasonable goals.

Within the next ten years, MEMS systems will provide applications in a variety of areas, including:

- Remote environmental monitoring and control, which can vary from sampling, analyzing, and reporting to doing on-site control. The applications could range from building environmental control to dispensing nutrients to plants.

- Dispensing known amounts of materials in difficult-to-reach places on an as-needed basis, which could be applicable in robotic systems.

- Automotive applications will include intelligent vehicle highway systems and navigation applications.

- Consumer products will see uses that allow the customer to adapt the product to individual needs. This will range from the automatic adjustment of a chair contour to measuring the quality and taste of water, and compensating for the individual requirements at the point of use.

To support the development of these products, an infrastructure has been established in the United States to exchange information, develop generic techniques for MEMS, and train students.

The structure in the United States does not have a central agency that coordinates and controls funding and/or research priorities. Individual government agencies have recognized the importance of MEMS and have supported the development of an infrastructure. The National Science Foundation was instrumental in advancing MEMS by establishing a Center of Excellence for Micromachining and supporting student attendance at conferences. Other government agencies, including the Advanced Research Projects Agency, the National Institutes of Health, the Department of Energy, the National Aeronautics & Space Administration, and the Department of Defense have all supported MEMS work at universities to advance their specific needs, and have underwritten student attendance at conferences. There has been extensive work at the national laboratories in MEMS for the environmental sensors. Sensors have been developed for water, air, and soil monitoring.

The professional engineering societies have been extremely supportive of MEMS work. The IEEE established the first workshop on solid-state sensors and actuators in 1984 and the MEMS conference in 1987. Today there are conferences supported by the ASME on MEMS as well as a joint IEEE/ASME journal on MEMS. These are both ongoing activities that allow for exchange of information among those active in the field of MEMS. Many of those first students are now active professionals in the MEMS field.

The government agencies have been very active in promoting cooperative research between industry and universities. The Center of Excellence requires that most of the funding come from outside the NSF. Conversion monies, those redirected from national defense, require that a commercial goal be established. MEMS in the United States has been very product oriented, with both large companies and small companies making significant advances. To expedite the availability of facilities to more universities and companies, the concept of a foundry system is receiving government support. Foundries are being established to allow proven integrated circuit structures to be manufactured, and then micromachining is performed at another facility. Institutions with minimal facilities can now do development in the MEMS area since they only need facilities for micromachining. Since proven integrated circuits will be used for the development, this should allow for faster development of concepts and devices.

The other area being supported by the government funding to universities is the CAD area for MEMS. To be able to do MEMS modeling requires the ability to do concurrent mechanical and electrical simulation. The present quality of MEMS modeling is one of the hindrances to fast commercialization of MEMS devices. To make modeling viable will require a data base of MEMS materials. There have been attempts by various organizations to compile data for general use. Since no central, recognized organization exists to perform this function, it has been done in an informal manner at conferences, workshops, and personal contact.

MEMS technology continues to grow in the United States, with expanded efforts in universities and research facilities. The commercialization of the technology is proceeding at a slower pace due to the need for companies to perceive the value to be gained by MEMS products. To date this has been in the high-volume sensor markets of the automotive and medical industries.

REFERENCES

Allen, H.V., S.C. Terry, and D.W. DeBruin. 1990. "Accelerometer Systems with Built-in Testing." *Sensors and Actuators.* A21-A23. Pp. 381-386.

Allen, M.G. 1993. "Polyimide-Based Processes for the Fabrication of Thick Electroplated Microstructures." *Digest of Technical Papers -- The 7th International Conference on Solid-State Sensors and Actuators (Transducers '93).* Pp. 60-65.

Baer, W.G., T. Hull, K. Najafi, and K.D. Wise. 1991. "A Multiplexed Silicon Infrared Thermal Imager." *Digest IEEE Int. Conf. on Solid-State Sensors and Actuators.* Pp. 631-634.

Baltes, H., and D. Moser. 1993. "CMOS Vacuum Sensors and Other Applications of CMOS Thermopiles." *Digest Int. Conf. on Solid-State Sensors and Actuators.* Pp. 736-741.

Barth, P., et al. 1988. "A Monolithic Silicon Accelerometer with Integral Air Damping and Overrange Protection." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 35-38.

Bernstein, J. 1992. "A Micromachined Condenser Hydrophone." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 161-165.

Bernstein, J., S.T. Cho, A.T. King, A. Koutrpenis, P. Maciel, and M. Weinberg. 1993. "A Micromachined Comb-Drive Tuning Fork Rate Gyroscope." *Digest IEEE Microelectromechanical Systems Workshop.* Pp. 143-148.

Boxenhorn, B., and P. Greiff. 1990. "Monolithic Silicon Accelerometer." *Sensors and Actuators.* A21-A23. Pp. 273-277.

Cho, S.T., and K.D. Wise. 1993. "A High-Performance Microflowmeter with Built-In Self-Test." *Sensors and Actuators.* A. Pp. 47-56.

Choi, I.H., and K.D. Wise. 1986. "A Silicon Thermopile-Based Infrared Sensing Array for Use in Automated Manufacturing." *IEEE Trans. on Electron Devices.* 33, January: 72-79.

Greiff, P., B. Boxenhorn, T. King, and L. Niles. 1991. "Silicon Monolithic Micromechanical Gyroscope." *Digest Int. Conf. on Solid-State Sensors and Actuators (Transducers '91).* Pp. 966-968.

Guckel, H., D.W. Burns, C.R. Rutigliano, D.K. Showers, and J. Uglow. 1987. "Fine-Grained Polysilicon and its Application to Planar Pressure Transducers." *Digest Int. Conf. on Solid-State Sensors and Actuators (Transducers '87).* Pp. 277-282.

Guckel, H., T.R. Christenson, K.J. Skrobis, J. Klein, and M. Karnowsky. 1993a. "Design and Testing of Planar Magnetic Micromotors Fabricated by Deep X-Ray Lithography and Electroplating." *Digest of Technical Papers - The 7th International Conference on Solid-State Sensors and Actuators (Transducers '93).* Pp. 76-79.

Guckel, H., M. Nesnidal, J.D. Zook, and D.W. Burns. 1993b. "Optical Drive/Sense for High-Q Resonant Microbeams." *Digest of Technical Papers -- The 7th Int. Conf. on Solid-State Sensors and Actuators (Transducers '93).* Pp. 686-689.

Guckel, H., K.J. Skrobis, J.Klein, T.R. Christenson, and T. Wiegele. 1993c. "Deep X-Ray Lithography for Micromechanics." In *Proceedings of Québec '93 -- SPIE International Symposium on Holography, Microstructures, and Laser Technologies.*

Guckel, H., et. al. 1992. "Polysilicon Resonant Microbeam Technology for High Performance Sensor Applications." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 153-156.

Henrion, W., et al. 1990. "Wide Dynamic Range Direct Digital Accelerometer." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 153-157.

Howe, R.T., and R.S. Muller. 1986. "Resonant-Microbridge Vapor Sensor." *IEEE Trans. Electron Devices.* ED-33. Pp. 499-506.

Huff, M.A., J.R. Gilbert, and M.A. Schmidt. 1993. "Flow Characteristics of a Pressure-Balanced Microvalve." *Digest of Technical Papers -- The 7th International*

Conference on Solid-State Sensors and Actuators (Transducers '93). Pp. 98-101.

Jerman, J.H., D. Clift, and S.R. Mallinson. 1990. "A Miniature Fabry-Perot Interferometer with a Corrugated Silicon Diaphragm Support." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 140-144.

Ji, J., and K.D. Wise. 1992. "An Implantable CMOS Circuit Interface for Multiplexed Microelectrode Recording Arrays." *IEEE J. Solid-State Circuits,* 27, March: 433-443.

Kim, E.S., J.R. Kim, and R.S. Muller. 1991. "Improved IC-Compatible Piezoelectric Microphone and CMOS Process." *Digest IEEE Int. Conf. on Solid-State Sensors and Actuators.* Pp. 270-273.

Kim, C.-J., A.P. Pisano, R.S. Muller, and M.G. Lim. 1990. "Design, Fabrication and Testing of a Polysilicon Microgripper." *Microstructures, Sensors, and Actuators, DSC-Vol. 19, ASME Winter Annual Meeting.* Pp. 99-109.

Kong, L.C., B.G. Orr, and K.D. Wise. 1993. "An Integrated Electrostatically-Resonant Scan Tip for an Atomic Force Microscope." *Journal of Vacuum Science and Technology,* B, May/June: 634-641.

MacDonald, N.C. 1993. "Nanomechanisms and Tips for Microinstruments." *Digest of Technical Papers -- The 7th International Conference on Solid-State Sensors and Actuators (Transducers '93).* Pp. 8-12.

Mallon, J., et al. 1990. "Low-Pressure Sensors Employing Bossed Diaphragms and Precision Etch-Stopping." *Sensors and Actuators.* A21-23: 89-95.

Mastrangelo, C., and R.S. Muller. 1991. "Fabrication and Performance of a Fully-Integrated μ-Pirani Pressure Gauge with Digital Readout." *Digest Int. Conf. on Solid-State Sensors and Actuators (Transducers '91).* Pp. 245-248.

Mulhern, G.T., D.S. Sloane, and R.T. Howe. 1993. "Supercritical Carbon Dioxide Drying Of Microstructures." *Digest of Technical Papers -- The 7th International Conference on Solid-State Sensors and Actuators (Transducers '93).* Pp. 296-299.

Muller, R.S. 1990. "Microdynamics." *Sensors and Actuators.* A21:1.

Najafi, N., and K.D. Wise. 1990. "An Organization and Interface for Sensor-Driven Semiconductor Process Control Systems." *IEEE Journal of Semiconductor Manufacturing.* November: 230-238.

Nathanson, H.C., W.E. Newell, R.A. Wickstrom, and J.R. David Jr. 1967. "The Resonant Gate Transistor." *IEEE Trans. Electron Devices.* ED-14: 117-133.

Nguyen, C.T.-C., and R.T. Howe. 1992. "Quality-Factor Control for Micromechanical Resonators." *Digest Int. Electron Devices Meeting.* December: 505-508.

Nomoto, T. 1993. "A 2/3-inch 2M-Pixel CMD Image Sensor with Multi-Scanning Function." *Digest IEEE Int. Solid-State Circuits Conf.* February: 196-197.

Ohnstein, T., et al. 1990. "Environmentally-Rugged Wide Dynamic Range Microstructure Airflow Sensor." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 158-160.

Parameswaran, L., V.M. McNeil, M.A. Huff, and M.A. Schmidt. 1993. "Sealed-Cavity Microstructure using Wafer Bonding Technology." *Digest of Technical Papers -- The 7th International Conference on Solid-State Sensors and Actuators (Transducers '93).* Pp. 274-277.

Payne, R.S., and K.A. Dinsmore. 1991. "Surface Micromachined Accelerometer: A Technology Update." *Digest SAE Meeting.* Pp. 127-135.

Petersen, K.E. 1982. "Silicon as a Mechanical Material." *Proc. IEEE.* 70, May: 420-457.

Petersen, K., et al. 1991. "Resonant Beam Pressure Sensor Fabricated with Silicon Fusion Bonding." *Digest Int. Conf. on Solid-State Sensors and Actuators (Transducers '91).* Pp. 664-667.

Petersen, K., et al. 1988. "Silicon Fusion Bonding for Pressure Sensors." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 144-147.

Pourahmadi, F., L. Christel, and K. Petersen. 1992. "Silicon Accelerometer with new Thermal Self-Test Mechanism." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 122-125.

Ristic, L., et al. 1992. "Surface Micromachined Polysilicon Accelerometer." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 118-121.

Sampsell, J.B. 1993a. "The Digital Micromirror Device and Its Application to Projection Displays." *Technical Digest, Transducers '93.* Pp. 24-27.

Sampsell, J.B. 1993b. "The Digital Micromirror Device and Its Application to Projection Display." *Digest of Technical Papers -- The 7th International*

Conference on Solid-State Sensors and Actuators (Transducers '93). Pp. 24-27.

Tai, Y.C., R.S. Muller, and R.T. Howe. 1985. "Polysilicon Bridges for Anemometer Applications." *Digest Int. Conf. on Solid-State Sensors and Actuators (Transducers '85).* Pp. 354-357.

Tang, W.C., T.-C.H. Nguyen, and R.T. Howe. 1989. "Laterally Driven Polysilicon Resonant Microstructures." *Sensors and Actuators.* 20: 25-32.

Tanghe, S.J., and K.D. Wise. 1992. "A 16-Channel CMOS Neural Stimulating Array." *IEEE Journal of Solid-State Circuits*, 27, December: 1819-1825.

Terry, S.C. 1988. "A Miniature Silicon Accelerometer with Built-in Damping." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 114-116.

U.S. Patent #5,013,693. 1991. "Formation of Microstructures with Removal of Liquid by Freezing and Sublimation." 7 May.

Wise, K.D. 1993. "Integrated Microinstrumentation Systems: Smart Peripherals for Distributed Sensing and Control." *Digest 1993 IEEE International Solid-State Circuits Conf.* Pp. 126-127.

Wise, K.D., and N. Najafi. 1991a. "The Coming Opportunities in Microsensor Systems." *Digest IEEE Int. Conf. on Solid-State Sensors and Actuators.* Pp. 2-7.

Wise, K.D., and K. Najafi. 1991b. "Microfabrication Techniques for Integrated Sensors and Microsystems." *Science*, 254, 29 November: 1335-1342.

Wood, R.A., C.J. Han, and P.W. Kruse. 1992. "Integrated Uncooled Infrared Detector Imaging Arrays." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 132-135.

Yun, W., R.T. Howe, and P.R. Gray. 1992b. "Surface Micromachined Digitally Force-Balanced Accelerometer with Integrated CMOS Detection Circuitry." *Digest IEEE Solid-State Sensor and Actuator Workshop.* Pp. 126-129.

Zdeblick, M.J., and J.B. Angell. 1987. "A Microminiature Electric-to-Fluidic Valve." *Transducers '87, 4th Int. Conf. Solid-State Sensors and Actuators.* Pp. 827-829.

Ziaie, B., J. Von Arx, M. Nardin, and K. Najafi. 1993. "A Hermetic Packaging Technology with Multiple Feedthroughs for Integrated Sensors and Actuators." *Digest of Technical Papers -- The 7th International Conference on Solid-State Sensors and Actuators (Transducers '93).* Pp. 266-269.

A SELECTED BIBLIOGRAPHY OF RECENT U.S. RESEARCH ON MICROACTUATORS

Comb Drives

Fan, L.-S., and L. Crawforth. 1992. "'Spring-Softening' Effect in MEMS Microstructures." *Technical Digest, Transducers '93.* Pp. 767-770.

MacDonald, N.C. 1992. "Single Crystal Silicon Nanomechanisms for Scanned-Probe Device Arrays." *Technical Digest, IEEE Solid-State Sensor and Actuator Workshop.*

Tang, W.C., M.G. Lim, and R.T. Howe. 1992. "Electrostatic Comb Drive Levitation and Control Method." *J. Microelectromechanical Systems.* 1, 4: 170-178.

Resonators

Boustra, S., H.A.C. Tilmans, A. Selvakumar, and K. Najafi. 1992. "Base Driven Micromechanical Resonators." *Technical Digest, IEEE Solid-State Sensor and Actuator Workshop.* Pp. 148-152.

Lee, A.P., P.B. Ljung, and A.P. Pisano. 1992. "Polysilicon Microvibromotors." *Proc. IEEE Microelectromechanical Systems Workshop.* Pp. 177-182.

Nguyen, T.-C.H., and R.T. Howe. 1993. "Microresonator Frequency Control and Stabilization Using an Integrated Micro Oven." *Technical Digest, Transducers '93.* Pp. 1040-1043.

Rotating Micromotors

Deng, K., V.R. Dhuler, and M. Mehregany. 1993. "Measurement of Micromotor Dynamics in Lubricating Fluids." *Proc. IEEE Microelectromechanical Systems Workshop.* Pp. 260-264.

Dhuler, V.R., M. Mehregany, S.M. Phillips, and J.H. Lang. 1992. "A Comparative Study of Bearing Designs and Operational Environments for Harmonic Side-Drive Micromotors." *Proc. IEEE Microelectromechanical Systems Workshop.* Pp. 171-176.

Dhuler, V.R., M. Mehregany, and S.M. Phillips. 1992. "Micromotor Operation in a Liquid Environment." *Technical Digest, IEEE Solid-State Sensor and Actuator Workshop.* Pp. 10-13.

Huang, J.B., P.S. Mao, Q.Y. Tong, and R.Q. Zhang. 1993. "Study on Si Electrostatic and Electro-Quasi-Static Micromotors." *Sensors and Actuators.* 35, 3: 171-174.

Kumar, S., and D. Cho. "Electrostatically-Levitated Microactuators." 1992. In *Micromechanical Systems.* Pp. 53-68. (Paper presented at the Winter Annual Meeting of the ASME, 8-13 November, Anaheim, CA.)

Mehregany, M., M.P. Omar, and R.L. Mullen. 1992. "Analysis of Motive Force, Axial Torque, and Viscous Drag Torque in Side-Drive Micromotors." In *Micromechanical Systems.* Pp. 133-148. (Paper presented at the Winter Annual Meeting of the ASME, 8-13 November, Anaheim, CA.)

Friction and Sticking

Alley, R.L., P. Mai, K. Komvopoulos, and R.T. Howe. 1993. "Surface Roughness Modification of Interfacial Contacts in Polysilicon Microstructures." *Technical Digest, Transducers '93.* Pp. 288-291.

Deng, K., W.H. Ko, V.R. Dhuler, M. Mehregany, S.M. Phillips, and J.H. Lang. 1992. "A Comparative Study of Bearing Designs and Operational Environments for Harmonic Side-Drive Micromotors." *Proc. IEEE Microelectromechanical Systems Workshop.* 35, 1: 171-176.

Tavrow, L.S., S.F. Bart, and J.H. Lang. 1992. "Operational Characteristics of Microfabricated Electric Motors." *Sensors and Actuators.* 35, 1: 33-44.

Magnetic Drive

Ahn, C.H., and M.G. Allen. 1992. "A Fully-Integrated Micromagnetic Actuator With a Multilevel Meander Magnetic Core." *Technical Digest, IEEE Solid-State Sensor and Actuator Workshop.* Pp. 14-18.

Allen, M.G. 1993. "Polyimide-Based Processes for the Fabrication of Thick Electroplated Microstructures." *Technical Digest, Transducers '93.* Pp. 60-65.

Busch-Vishniac, I.J. 1992. "The Case for Magnetically Driven Microactuators." *Sensors and Actuators.* 33, 3: 207-220.

Guckel, H., T.R. Christenson, K.J. Skrobis, T.S. Jung, J. Klein, K.V. Hartojo, and I. Widjaja. 1993. "A First Functional Current Excited Planar Rotational Magnetic Micromotor." *Proc. IEEE Microelectromechanical Systems Workshop.* Pp. 7-11.

Ultrasonic Drive

Moroney, R.M., R.M. White, and R.T. Howe. 1991. "Ultrasonically Induced Microtransport With Cylindrical Geometry." *Micromechanical Sensors, Actuators, and Systems*. Pp. 181-190.

Piezoelectric Drive

Flynn, A.M., L.S. Tavrow, S.F. Bart, R.A. Brooks, D.J. Ehrlich, K.R. Udayakumar,and L.E. Cross. 1992. "Piezoelectric Micromotors for Microbots." *J. of Microelectromechanical Systems*. 1, 1:44-51.

Lal, A., and R.M. White. 1993. "Micro-Fabricated Acoustic and Ultrasonic Source/Receiver." *Technical Digest, Transducers '93*. Pp. 712-715.

Schiller, P., and D.L. Polla. 1993. "Integrated Piezoelectric Microactuators Based on PZT Thin Films." *Technical Digest, Transducers '93*. Pp. 154-157.

Microactuated Electrooptic Devices

Hung, C.-Y., R. Burton, T.E. Schlesinger, M.L. Reed, S.C. Smith, D.J. Holmgren, and R.D. Burnham. 1992. "Microelectromechanical Tuning of Electrooptic Devices." *Proc. IEEE Microelectromechanical Systems Workshop*. Pp. 154-157.

Sandejas, F.S.A., R.B. Apte, W.C. Banyai, and D.M. Bloom. 1993. "Surface Microfabrication of Deformable Grating Light Valves for High Resolution Displays." *Technical Digest, Transducers '93*. Pp. 6-7.

APPENDIX E. GLOSSARY

ADC	Analog-to-Digital Convertor
AES	Auger Electron Spectroscopy
AFM	Atomic Force Microscope
AGC	Automatic Gain Control
ARPA	Advanced Research Projects Agency (U.S. Govt.)
ATM	Asynchronous Transfer Mode; also, Atmosphere (1 ATM = 760 mmHg)
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CCD	Charge-Coupled Device
CEBOT	Cellular Robot
CMOS	Complementary Metal-Oxide Semiconductor
CNC	Computerized Numerical Control
CVD	Chemical Vapor Deposition
DEMA	Distributed Electromechanical Actuator
DIP	Dual In-line Package
DP	Differential Pressure
ECR	Electron Cyclotron Resonance
EDM	Electro-Discharge Machining
EM	Electro-Magnetic

EPROM	Electronically (Re)Programmable Read-Only Memory
ETL	Electro-Technical Laboratory (MITI)
FEM	Finite Element Method
FIB	Focused Ion Beam
FL	Fuzzy Logic
FPD	Flat Panel Display
HF	Hydrofluoric Acid
HVAC	Heating, Ventilation, and Air Conditioning
IC	Integrated Circuit
IDMTM	Information Driven Machines that Move
IR	Infra-Red
ISFET	Ion-Sensitive Field Effect Transistor
IWD	Integrated Waveguides by Compositional Disordering
KOH-Based	Potassium Hydroxide-Based
LAN	Local Area Network
LIGA	in German: Lithographie Galvanoformung Abformung (a process based on lithography, electroplating, and molding)
MCM	Multi-Chip Module
MCNC	Microelectronics Center of North Carolina
MEL	Mechanical Engineering Laboratory (MITI)
MEMCAD	Microelectromechanical Computer-Aided Design (Design program under development at the Massachusetts Institute of Technology)
MEMS	Microelectromechanical Systems

MITI	Ministry of International Trade and Industry (Japan)
MLE	Molecular Layer Epitaxy
MMC	Micromachine Center (Japan)
MOS	Metal Oxide Semiconductor
MOSIS	A U.S. integrated circuit foundry service
NEDO	New Energy and Industrial Technology Development Organization (Japan)
NETD	Noise Equivalent Temperature Difference
NIH	National Institutes of Health
NMOS	N-Channel Metal Oxide Semiconductor (a transistor technology)
NRLM	National Research Laboratory for Metrology
OD	Outer Diameter
PAT	Packaging, Assembly and Testing
pCO_2	Partial pressure of Carbon dioxide
PGA	Pin Grid Array
Piezoactuator	An actuator typically producing a force or displacement in response to an electrical input signal
PLZT	Variation of PZT
PMMA	Poly Methyl Methacrylate (an electron-beam and X-ray sensitive resist)
PVDF	Polyvinylidene Fluoride
PZT	Lead Zirconate Titanate
QMS	Quadrapole Mass Spectroscopy
RCAST	Research Center for Advanced Science and Technology

RDT	Rotary Displacement Transducer
RF	Radio Frequency
RHEED	Reflection High Energy Electron Diffraction
RIE	Reactive Ion Etch
SAS	Sensors, Actuators, and Subsystems
SEM	Scanning Electron Microscope
SIMS	Secondary Ion Mass Spectroscopy
SLR	Single-Lens Reflex (camera)
SMA	Shaped Memory Alloy
SOI	Silicon-on-Insulator
SRAM	Static Random Access Memory
STM	Scanning Tunneling Microscope
TFT	Thin Film Transistor
TIG	Tungsten Inert Gas (a type of welding)
ULSI	Ultra Large-Scale Integration
UV	Ultraviolet
VLSI	Very Large-Scale Integration
VSM	Very Small Machines
WCVD	Tungsten Chemical Vapor Deposition
WEDG	Wire Electric Discharge Grinding
XPS	X-ray Photo-Spectroscopy

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